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SHIELD AND COMPRESSED AIR TUNNELING

Under the Hudson River, New York. Rock in the bottom and silt in the upper part of the face. ***(Frontispiece)***
(Courtesy *of Hudson and Manhattan Railroad*)

SHIELD AND COMPRESSED AIR TUNNELING

BY

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AND

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SOMETIME ENGINEER ON THE CONSTRUCTION OF THE ISLINGTON EXTENSION TO THE CITY & SOUTH LONDON RAILWAY, OF THE PENNSYLVANIA RAILROAD TUNNELS, NEW YORK, AND OF THE MANHATTAN ELEVATED RAILROAD IMPROVEMENTS AND EXTENSIONS FOR THE INTERBOROUGH RAPID TRANSIT COMPANY, NEW YORK.

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PREFACE

At least two valuable books on shield tunneling have been written. The first was published in Paris in the year 1897. The author was R. Legouez and the title "De l'Emploi de Bouclier dans la Construction des Souterrains." The second was published in London in the year 1906. The author was W. C. Copperthwaite and the title "Tunnel Shields and the Use of Compressed Air in Subaqueous Works." Besides these two books and several others dealing largely, however, with tunneling in general rather than with the special subject of shield tunneling, a great number of papers to engineering societies and institutions and of articles in the technical press have appeared. In most of these scattered writings the matter has consisted, for the most part, of descriptions of the methods used and the work done on specific instances of tunnel construction.

Why was this book written? So much tunneling has been done with the aid of the shield and the art of such work has been developed to such a point that it is possible now to formulate, to some extent at least, certain principles and rules of practice on which to base the design and construction methods of future work. At the suggestion of F. E. Schmitt, Associate Editor of *Engineering News-Record*, and with his help, this is what the authors have tried to do.

The writers of such a book must be under a deep debt of gratitude to all engineers who have left a written record of their work. This debt is freely and thankfully acknowledged.

The Pennsylvania Railroad Company, through Samuel Rea, President, has authorized the publication of the important facts in connection with its Hudson River tunnels, particularly those detailed on page 349.

These facts have been obtained by an unbroken series of observations commenced during the construction of the tunnels, under the direction of the Chief Engineer, C. M. Jacobs, and of the Chairman of the Board of Engineers, Brig. Gen. C. W. Raymond, and continued up to the present time under the direction of James Forgie, Consulting Engineer, who was Chief Assistant Engineer during the construction.

The importance of this information to the profession is great and the authors are deeply indebted to the Pennsylvania Railroad for permitting its publication through the medium of this book.

In addition our grateful thanks are especially due to the following: J. Vipond Davies of New York, Consulting Engineer, who has opened to us freely the tunnel records of his office and who has helped in many other ways; Robert Ridgway, Chief Engineer of the Rapid Transit Commission of New York, who has given information and photographs relating to the recent tunnels crossing the East River for the New York subways; Howard E. Boardman, formerly Assistant Engineer on the construction of the Hudson River tunnels of the Pennsylvania Railroad, who made suggestions in connection with the chapter on Tunnel Surveys; W. C. Copperthwaite, Chief Engineer to the London County Council, for permission to use illustrations from his book "Tunnel Shields," which mine of useful information has been used freely by the authors; Colonel F. A. Snyder, General Resident Engineer, New York-New Jersey vehicular tunnel under the Hudson River, for suggestions, particularly as to the chapters on Plant, and Dr. Edward Levy, Physician to the Transit Commission, New York City, for invaluable help in the chapter on compressed air illness.

B. H. M. Hewett.
S. Johannesson.

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SHIELD AND COMPRESSED AIR TUNNELING

CHAPTER I

INTRODUCTION

The work described in this book is of quite recent growth. In the year 1879 compressed air was first applied to tunnel work, in 1886 the first iron-lined, shield driven tunnel of the modern type was built. The scope and importance of tunneling are increasing constantly as our cities grow in size and wealth. From year to year tunnels are needed for Railways, Highways, Rapid Transit, Water Supply, Sewage Disposal, Gas Supply and other purposes, and the shield method frequently will be found useful and even necessary for the construction of these tunnels. As the population grows the size and number of the tunnels required tend to become greater and greater. What was impossibly large to one generation is a commonplace to the next.

Tunneling is a branch of Engineering, therefore, which the student, whether still in college or grown gray in bending the forces of nature to the use and benefit of mankind, cannot and must not neglect. No matter what his special branch may be, the engineer may be called upon to take his part in the construction of a tunnel or in deciding whether he shall or shall not build a tunnel, and if so, by what method he shall build it. He may be the chief on whose shoulders rest the responsibilities of making the final decision and of directing the efforts of a staff of experts, or he may be a youngster fresh from college, serving his first term as a draftsman, inspector or rodman on the design or construction of such a tunnel.

In most branches of the civil engineering art practice and theory have advanced hand in hand to such a point that the subject may be said to have reached virtual standardization. By this is meant, not that the ultimate has been reached—far from it; but that a wealth of written testimony exists which will guide the engineer along the safe path and ensure practical success.

Quite the reverse is true in shield and compressed air tunneling. Important though the subject, there is little written which attempts to garner the fruit of the large body of experience which

has accrued and from that experience to deduce some general rules of theory and practice as a stepping stone to the standardization of the art. No doubt, there may be good reason for this. The subject is one of great complexity. There is a bewildering array of conditions and combination of conditions to be considered and it seems that the engineer may have been deterred by this very complexity and have been content to look upon each tunnel problem that has arisen as a special case. Nevertheless, this has reacted on tunnel construction as well as on the tunnel engineer. Tunnels are often considered only as a last resort and the tunnel engineer as a rule-of-thumb artisan. Both of these views are wrong and the aim of this book is to help to change them.

The particular kind of tunnel dealt with in this book is that in which the tunneling shield or the use of compressed air or the two in combination are indicated. In other words, it covers the difficult work of tunneling through soft or waterbearing ground.

In tunneling, the ground to be penetrated may be the hardest rock or the softest mud. It may consist of any variety between these two. It may be below the level of ground water or even below a waterway. How are we to design the tunnel, be its purpose what it may? How are we to design the shield? What plant do we need? What force of men will be required? What progress shall we make? How shall we carry out the work of construction? What will the tunnel cost? What methods of survey will ensure our tunnel being where we want it? What precautions must we use to reduce to a minimum the dread sickness that walks in compressed air? These are some of the questions answered in this book.

In tunneling with the shield, more so than in any other branch of engineering, it is the engineer's function to direct the work, not only in general terms, but even down to the smallest details. Whoever has been privileged to have charge of the construction of a shield driven tunnel will know that, after the location has been fixed, the design made and the work started, he will be charged with a never ceasing load of cares that cannot be left to the contractor, however proficient, efficient or experienced the latter may be. To start with, every move of the very shield is in itself an experiment which must be controlled and directed by the engineer. Every change of ground demands a change in the methods of construction. It is the engineer's duty to know

beforehand where these changes will occur and to be prepared for them and not merely wait for them to show themselves. It is he who must direct what exploratory borings must be made to predetermine these changes of ground and it is he who must know what methods are best suited to the conditions thus disclosed. He must have knowledge of the proper air pressure to carry under a given set of conditions; he must know where the bulkheads should be built; he must be prepared, in fact, to give to every phase of the work the most broad and basic directions and at the same time to see that in the minutest details the work is conducted so as to give the best possible result that the circumstances will allow. Heavy, indeed, is his load of care. He owes it to his clients and equally to his own conscience that his location, design and direction are such that the work is sound and permanent, built with due economy of money, time and labor and that the lives of those who are carrying out the work may not be endangered by collapse, flood or disease.

These pages are rather a pioneer effort to place the art of shield tunneling on a rational basis. If they give help to any fellow engineer who, by choice or by fate, follows the art of tunneling, the authors will feel repaid indeed.

CHAPTER II

TUNNELING

1. Purpose of Tunnels.—Except in connection with mining operations tunnels are built for one purpose only, namely transportation. The objects to be transported may be persons, vehicles or any solid, liquid or gaseous matter.

2. Choice of Tunnel.—The surface of the earth is the natural place on which to transport matters, but sometimes there is an obstacle in the way which prevents or makes economically impossible the use of the surface for all or specific kinds of transportation. The obstacle may be a hill, a waterway or a crowded city. If the obstacle is a hill, the only solution is to build a tunnel. If the obstacle is city traffic or a waterway, there may be a choice between carrying the line above the surface on a bridge or elevated structure or below the surface in a tunnel. In city streets public opinion rather than engineering economics will determine the choice. The prevailing tendency is to carry underground those lines which cannot be carried on the surface, except possibly in outlying districts.

3. Crossing of Waterways.—As regards the crossing of rivers or waterways, it is largely the custom and habit to think in terms of bridges, the possibility of using tunnels being overlooked. This trend of thought has survived from the time, not so very long ago, when rock tunneling was carried out precariously by alternate applications of fire and water and when tunneling through open waterbearing ground practically was beyond the capability of man. Those times have passed. It is now possible to tunnel through any kind of ground.

4. Tunnel or Bridge.—In any given case, therefore, involving the provision of a crossing of a waterway, the final decision as to the type of structure should be reached only after the comparative advantages and disadvantages of both tunnels and bridges have been considered. There are cases where a bridge is out of the question, but where a tunnel might be provided. There are other cases where a tunnel equally evidently is impossible, but where a bridge is feasible. In many cases, however, an alterna-

tive choice is possible and in these cases a comparative study should be made. The proper selection is largely a matter of economy. The cost of a bridge will be approximately proportional to the number of traffic lines it carries, but the cost per unit length of the bridge will rapidly increase with the length of the span. The cost of a tunnel, on the other hand, will usually be less per unit length, the longer it is, because the plant and other overhead charges are distributed over a greater length; but the cost per traffic line will increase with the number of traffic lines carried. This latter disadvantage may frequently be remedied, however, by separating the traffic lines and carrying them in two or more smaller tunnels. A tunnel, therefore, will often compare favorably in cost with a bridge, and it is not an obstruction to the waterway. Neither is the traffic in the tunnel subject to periodic stoppage as is the case with swing or bascule bridges.

5. Special Conditions.—Certain cases may not admit of purely engineering or economic solutions. It may be desired to build a bridge as a memorial of some great event. In that case the whole merit of the scheme lies in the fact that the bridge is visible. Even though a tunnel might be the logical engineering choice, it would not be acceptable, as it could not be seen from a distance, and therefore could not make the same appeal to the imagination. On the other hand, it should not be forgotten that in time of war a bridge is one of the most vulnerable objects of the enemy's fire, while a tunnel is comparatively safe from destruction. The "tubes" of London afforded safe haven for thousands while the Zeppelins were dropping bombs and the guns of the defence were searching the darkness for their target.

6. Types of Tunnels.—During the progress of the art of tunneling several types of tunnels have been developed which may be classified as follows, according to the methods used in carrying out the work of construction.

CLASS I. TRUE TUNNELS (SURFACE NOT DISTURBED)

I-A. Mining (and timbering if necessary) in normal air.
I-B. Mining (and timbering if necessary) in compressed air
I-C. Complete Tunnel Shield in normal air.
I-D. Complete Tunnel Shield in compressed air.
I-E. Roof Shield in normal air.

I-F. Roof Shield in compressed air.
I-G. Freezing and mining.

CLASS II. PSEUDO TUNNELS (SURFACE DISTURBED)

II-A. Cut-and-Cover in normal air.
II-B. Cofferdam, in normal air.
II-C. Trench, in normal air.
II-D. Caisson, in compressed air.

7. Selection of Type.—The selection of type to use in any given instance depends on the condition of the ground and on the facilities of construction. Class I tunnels are constructed without disturbing the surface of the ground and compressed air is used in their construction when the ground is waterbearing and in some instances to assist in supporting the excavation. Class II tunnels are permissible where the surface may be occupied during the construction period. Generally speaking the selection of each type of tunnel may be indicated as follows.

I-A. Mining and Timbering in Normal Air.—Suitable for dry ground, particularly in rock, stiff clay and similar ground.

I-B. Mining and Timbering in Compressed Air.—Suitable in wet cohesive ground, which may be dried out by the compressed air. If much timbering is needed shield tunneling may be preferable.

I-C. Complete Tunnel Shield in Normal Air.—Suitable for dry swelling or running ground.

I-D. Complete Tunnel Shield in Compressed Air.—Suitable for any kind of waterbearing ground.

I-E. Roof Shield in Normal Air.—Suitable instead of mining and timbering in dry ground when the extent of the work warrants the cost of the shield.

I-F. Roof Shield in Compressed Air.—Suitable instead of mining and timbering in waterbearing ground, permitting this method, when the extent of the work warrants the cost of the shield.

I-G. Freezing and Mining.—Method as yet undeveloped. Recommended only as a last chance.

II-A. Cut-and-Cover.—Suitable where the ground is dry and the cover shallow.

II-B. Cofferdam.—Suitable in shallow water and with shallow cover, particularly when the work is limited in length.

II-C. Trench.—Suitable under water when the cover is shallow. In open ground with very shallow cover the method may be more economical than shield tunneling.

II-D. Caisson.—For limited tunnel construction in waterbearing ground. Suitable where the tunnel structure is too complicated for shield tunneling.

CHAPTER III

THE TUNNEL MINER'S ART

1. Effect of Shield on Mining Methods.—As will be seen later the shield method and the use of compressed air have not supplanted the earlier mining methods, but have merely made easier the task of the miner, reduced the risk, increased the speed and thus lowered the cost of penetrating the ground. The more difficult the ground from the miner's point of view, the more applicable the shield method and its faithful assistant, compressed air. To provide a background for much that follows it is necessary to devote a few pages to a description of the miner's art.

2. Origin of Mining Methods.—When our ancestor, the cave man, desired to extend his cave, he doubtless found that, as he dug further into the ground, the roof of his newly exposed tunnel developed an uncomfortable habit of dropping large chunks upon his head. It was natural then that he cut a stout tree and made a post to hold up the scaling roof. In some such way we may imagine that the methods of timbering a tunnel were initiated. Later, as men became acquainted with the metals and ores they needed for ornaments and use, they began to follow the veins from the surface into the ground, and the primitive methods of supporting the excavation were further developed.

3. Timbering of Tunnels.—In hard self-sustaining rock, mining is a matter solely of breaking the rock and transporting the debris to the mouth of the tunnel. In ground which is not self-supporting the problem of protecting the opening against the pressure of the ground, which is tending constantly to flow into the tunnel bore, is added to that of simple excavation and removal. When the ground is charged with water further difficulties are added, as the water has to be prevented from flowing into the bore in excessive quantity. Some soils, as for example when in the condition of "quick-sand," are really fluids ready to flow instantly into any opening made within them. Whenever the ground is not self-sustaining the miner must timber his excavation as he proceeds. In loose rock this timbering may be com-

paratively simple and confined to the roof. In real soft ground the timbering must consist of an unbroken surface extending over roof, sides, bottom and face. Each kind of ground has its own peculiar characteristics of weight and fluidity, and these will determine the method of excavation and timbering which is best adapted to the conditions presented.

4. Governing Conditions.—The miner's method will depend in the main on several chief factors as follows:

(*a*) the degree to which the ground is self-supporting;

(*b*) the degree to which the ground is free from, or charged with, water;

(*c*) the size (in cross-section) of the tunnel.

5. Self-supporting Dry Ground.—Suppose a case in which the factors are as follows: (*a*), the ground is quite self-supporting, (*b*), it is quite dry, (*c*) the size is such that a man can reach the entire height of the tunnel. This may be said to be the simplest possible case. It is merely necessary to excavate the ground and remove the spoil to the mouth.

6. Self-supporting Dry Ground, Large Excavation.—Now let us suppose that (*a*) the ground is self-sustaining, (*b*) it is dry, (*c*) the tunnel is so large that a man standing on the floor cannot reach the top. Here the only complication is afforded by the height of the tunnel. In such a case the work will consist of "heading" and "bench" work, whereas in the previous case there was nothing but heading work. In this second case a portion of the tunnel, it may be the top, the bottom or the middle section, will be driven first. The cross-section of this advanced work is such that men can work freely in it, which means that it will not be less than 6 or 7 ft. in height. The carrying out of this work is termed "driving the heading." Some distance behind the heading the rest of the cross-section of the tunnel simultaneously is excavated. This is termed "taking out the bench." The heading is always kept some distance ahead of the bench. Since most of this kind of tunnel work is in solid rock where the removal of the ground is done by blasting, it is becoming the habit to keep the heading and bench fairly close to one another, perhaps 12 ft. or so apart, so that by firing the shots in the heading and bench simultaneously the rock is thrown down into the same heap and may be removed all together. It is clear that by driving the heading and taking out the bench important advantages are gained. A greater number of men may be

employed at one time in excavating, as the men on the bench do not interfere with those at work in the heading, and the drill holes can be placed more effectively.

7. Ground Not Self-supporting, but Dry. Tunnel Small.—Now suppose that (*a*) the ground is not self-supporting, (*b*) it is dry, (*c*) the tunnel is so small in cross-section that a man standing on the floor can reach all parts of it. In this case the work will be all heading work, but the bore must be supported by timbering. This timbering will consist in general of a series of frames or "sets" of round or squared timber of cross-section having considerable strength, perhaps 10 in. in diameter if round or 8 by 8 in. if square. These sets will be placed at intervals of from 2 to 5 ft., depending on how "heavy" is the ground, and outside of the frames will be placed boards or planks, forming a sheathing or lagging. The boards take the thrust of the ground pressure and distribute the pressure to the sets. It is the function of the sets to withstand these pressures and thus prevent the opening from caving in.

8. Terms Used.—The lagging outside of the sets is termed poling in England. If boards are used they are termed "poling boards." The origin of this term dates from the primitive days of metal mining when small poles were used outside the sets. This was in the days when all sawing was done by hand and to make boards was not an easy matter. In the United States the term poling board is usually confined to boards driven ahead in wet or heavy ground, as will be described later, and the term lagging or sheathing used for boards placed outside the sets in ordinary dry or only moderately heavy ground. It seems useful to have distinctive names for each variety of lagging and in this book the following convention is used.

Lagging or sheathing means boards set round the top, sides and bottom of the main sets of a heading of a tunnel.

Poling boards means lagging which has to be driven forward in heavy or wet ground.

Breasting or breastboards means boards set against the vertical face of a heading or tunnel.

In a "square set heading" such as we are considering now, the various members are named as follows in this book (see Fig. 1). The top timber of the set is called *the Cap*. The two side timbers *Posts* and the bottom piece *the Sill*. In England the cap is known as "the headtree" and the posts as "the sidetrees." The

breasting is shown in Fig. 1 as supported by an upright *Soldier*, held in place by *a Raker*, which is a strut sloping back to the floor. In some ground it may not be necessary to use a sill. In that case the posts rest on *Footblocks* which are blocks of wood or short pieces of heavy plank which distribute the downward pressure of the posts and prevent them from sinking into the ground.

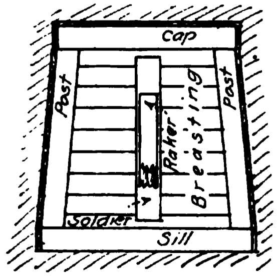


FIG. 1.—Square set heading in dry ground. Cross section.

9. Method of Timbering a Heading is Old.—It is interesting to note that Georgius Agricola of Saxony in his "De re metallica," published in the year 1550, after a period of 20 years of preparation, describes and illustrates with the quaintest of wood cuts methods of timbering shafts and tunnels which differ in no whit from those in use at the present day. The tools and appliances for excavating, transporting the spoil, pumping the water, furnishing ventilation and the like which he illustrates so profusely look tremendously crude and ineffective to the modern eye, but the miner of the present day would notice no difference in the finished timbering from that which he himself would use.

10. Ground Not Self-supporting and Wet, Small Heading.—We will now consider the condition where (*a*) the ground is not self-supporting, (*b*) the ground is wet, and (*c*) the tunnel is small. In other words, it may be a case of driving a heading through "quicksand." We will suppose that a shaft has been sunk to the required depth and that the next move is to "break out" with the heading along the line of the tunnel. The process will be about as follows (see Fig. 2). Inside the shaft a square set is placed. This will consist of stout round or square timbers and will be made of a cap *a*, supported at each end by a post *b*, and a sill *c*. The dimensions of this set will be such that a man can work conveniently within it—not less than 6 feet in the clear between cap and sill—and wide enough for two men to stand side by side between the posts. In extremely bad ground it may be necessary to reduce these dimensions, but it is obvious that, if the heading is reduced below a certain size, the work is greatly hampered and retarded. The miner is provided with a number of stout boards, 1½, 2 or 3 inches thick, depending on

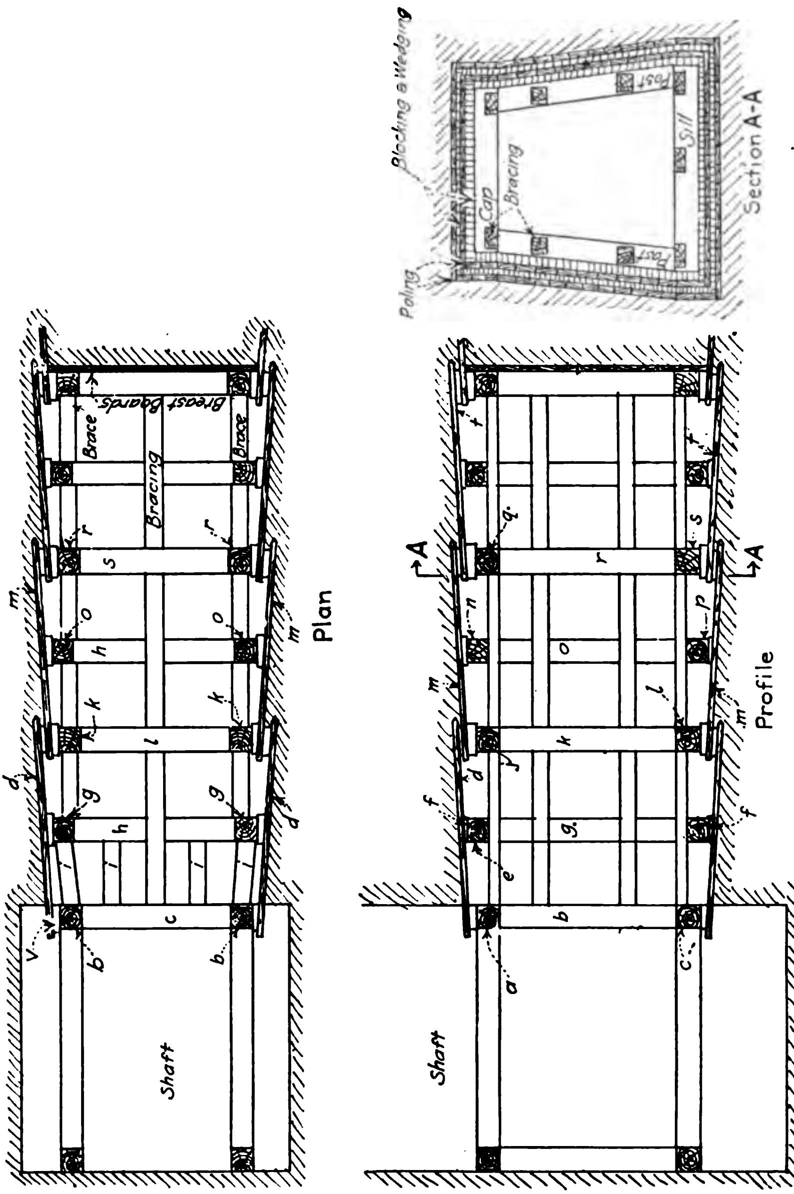


FIG. 2.—Square set heading in quicksand.

the dimensions of the heading, the character of the ground and similar conditions. These boards will be used to form the sheathing or skin around the sets. The miner must now decide how far apart he will place each set or frame of structural timber. Suppose he decides from what he has seen or knows of the ground that he can space his sets at 6 ft. centers. He now prepares his poling boards. These are cut from the boards mentioned and are made long enough to reach from, and overlap, the cap of one set to the cap of the next, plus an allowance. In this case he may cut his poling about 7 ft. 6 in. long.

11. Starting Heading.—Standing in the shaft he cuts away a piece of the sheathing which lines the shaft just over the cap of the heading set within the shaft. This piece is wide enough to take one of the poling boards. He spikes on top of the cap a piece of plank *v*, say 3 in. thick. The piece of shaft sheathing being cut out the poling board is then driven through the opening end on, the leading end being dressed down to a chisel point. During the driving the board rests on the 3-in. piece *v*, spiked to the top of the cap. The board is driven along the line of the future heading and is inclined upward at such a pitch that its under surface will be 6 or 7 in. above the top of the cap at the next set, which in this case will be 6 ft. ahead of the shaft set. When the first poling board has been driven, the driving being done with a sledge hammer, another piece of shaft sheathing is cut out alongside it and another poling board driven alongside the first. This is repeated until the entire width of the cap has been covered with a roof of poling boards which are now buried in the ground just like sheet piling. The plank *v* is now cut out and wedges driven tightly in its place. The same process is repeated down the outside of the posts, the poling being inclined outward in this case so as to be 6 or 7 in. outside the next set of the future heading. The same is done at the bottom, in this case the polings are inclined down to be 6 or 7 in. below the sill of the next set.

12. Opening Up.—There is now a rectangular palisade, as it were, of poling boards driven into the ground and enclosing the future heading. The miner now proceeds cautiously to cut away some of the shaft sheathing enclosed within the heading set in the shaft. He will begin at the top scraping away the ground underneath the roof polings. When he has cleared this out as far ahead as he can reach, perhaps 3 ft. out from the

shaft, he will set a supplementary cap *e*, wedging it at its ends against the side polings or securing it in any way he can, and will drive a series of wedges *f*, between the top of this cap and the under side of the roof poling. He now removes the earth little by little, preventing it from running toward the shaft by placing breast boards on the plane of the leading side of the cap *e*, and bracing this breasting back as best he can to the shaft timbering. Finally he will have excavated down to the bottom of the heading and he can place the sill *h* and on the sill the posts *g*. The poling boards on the side and bottom are wedged tightly against the outside of this supplementary frame and the heading is now fairly under way.

13. Closing Gaps in Poling.—There may be gaps and spaces between the poling boards through which the quicksand can find its way. These gaps are closed with wedges or pieces of wood, and hay, straw or similar substances are freely packed behind the boards or between them to make the sheathing tight. It may be desirable to bore some holes in the sheathing and force grout through by air pressure to solidify the ground and hold it from flowing, or the gaps may be plastered with tempered clay.

14. Continuing the Heading.—As soon as the supplementary set *egh* is in place it is firmly braced longitudinally against the shaft timbers by the braces *i*, *i*, *i*. The poling is now firmly supported at two places along its length, namely by the shaft set and by the supplementary set. The portion of the poling which projects beyond the set *egh* is still buried in the ground. The next stage is to break out beyond *egh* in the same way as originally done from the shaft set. The work is started at the top just as before and the earth is scraped away ahead of the cap *e* and underneath the roof poling *d*. When a distance of 6 feet has been reached from *a*, the cap *j* is put in place across the heading with its top surface 6 or 7 in. below the underside of *d*. The leading end projects a few inches or so beyond the cap *j*. When *j* has been set, wedged against the side poling and braced from the supplementary set *egh*, the polings *d* are wedged tight from the top of the cap *j*. Excavation is then carried on just as before to the vertical plane of the leading end of the cap *j*, breast boards being set and braced from the frame *egh* in the best way possible. When the excavation has reached the bottom, the sill *l* is set and braced from *h*. As each of these members is set the side and bottom polings are wedged tightly from them. The

closing of all crevices in the poling has proceeded concurrently with the uncovering of each board.

15. Advancing Another Length.—The heading has now been excavated and timbered as far as the set *jkl*. Everything is ready for the next advance. The wedges holding one of the roof poling boards *d* are taken out from over the cap *j* and a fresh roof poling is inserted in the gap so caused. This is driven ahead just as the original polings *d* were driven. When the first board *m* has been driven home, wedges are driven between *m* and *j* and between *m* and *d*. This second series of operations is in all respects like that for the first set. The supplementary set *nop* is placed, followed in due course by the second main heading set *qrs*.

16. Principle of Operation.—It is seen that the advance is made by successive steps, each one small in itself, and that the main principle is to open up the smallest possible extent of ground at a time, and to hold immediately every opening made from any possibility of movement. Not only must the pressure of the ground acting in a direction normal to the surface of the heading cross-section be resisted but there must be equal care taken against the thrust of the earth against the face of the heading and which acts in a direction along the longitudinal axis of the heading. This rough description of the work of a heading omits many details. It must be understood that much wedging and packing must be done as occasion arises. It is wonderful to see how regular and fine the work of the skilled miner is, how closely and evenly the main timbers bear one against the other and how close the poling is driven. The miner forces his way inch by inch ahead through ground pressures which are ever seeking to crush him and his work, and while he may know nothing of the theories of earth pressures he knows that the slightest carelessness on his part will set in motion gigantic and sleepless forces which may prove his instant destruction.

17. Ground not Self-supporting and Wet. Large Tunnel.—It is now supposed (*a*) that the ground is not self-supporting, (*b*) that it is waterbearing and (*c*) that the tunnel is large. In fact we will suppose that a railroad tunnel is to be driven through quicksand. As the cross-section is so large the method of first driving a heading and then enlarging to the full cross-section has to be adopted. The smaller the cross-section that is opened out at one time the less the risk of collapse and run, as the area

exposed is small and the difference in pressure between the top and bottom of the cross-section is comparatively small. The smaller this difference of pressure the less is the chance of the ground starting to move. While the miner, in such kinds of ground, has to deal with great pressures he can still feel fairly comfortable so long as the ground can be held from moving. Once it starts to move a critical situation is presented and this moving must be prevented from starting if the work is to go on without troubles greater than need be.

18. Starting the Work.—The principles of work in a heading as described in previous paragraphs applies to all the miner's work in soft ground. If he has to excavate a large cross-section it is done by opening out a length of heading first. A length means the length of tunnel which the miner considers he can safely excavate and carry on timbers until the lining is put in. In ordinary tunnel work without a shield the process consists first, of excavating and timbering a length, then building the permanent lining in that length, then excavating another length and so on in rotation until the entire tunnel has been excavated and lined. The work may proceed from one end, from both ends, from intermediate shafts or in any other way, the principle remains the same. The distance taken in one length depends on the character of the ground. In ordinary soft ground a length of 12 or 15 ft. may be said to be a usual case. In the heaviest kind of quicksand a shorter length, such as 5 feet may have to be taken.

19. Systems of Timbering.—There are several distinct systems of timbering which have been developed in various countries, each of which has its own particular merits. As this book is written for the English speaking engineer it may be enough to describe in general terms the American and the English systems, as they are most likely to be the two systems he will meet or require. No attention is given here to the German, Italian, French, Belgian, Austrian or other systems or combinations of timbering systems which various countries of the European continent have evolved to meet their particular needs. Any one who wishes to pursue this matter should consult Drinker's "Tunneling" which is an inexhaustible mine of such lore, filled with the finest of illustrations.

20. Difference between American and English Systems.—The broad difference between the American and the English

systems is that the American supports the roof by rafters or voussoirs set at right angles to the longitudinal axis of the tunnel and forming in effect a series of arches across the tunnel span. The English system carries the weight of the roof by a series of bars set around the periphery of the arch and carried at their ends by posts or props which in turn are carried by sills or bearing members set athwart the tunnel at the ends of the length. In this system, after the first length of lining has been built the rear ends of the bars for the next length are carried by the leading ends of the length of lining which has just been built. A sketch of the two systems will explain what is meant much better than a whole lot of words.

21. American System.—Figure 3 shows the American system. The segmental roof timbers are shown in this sketch as being

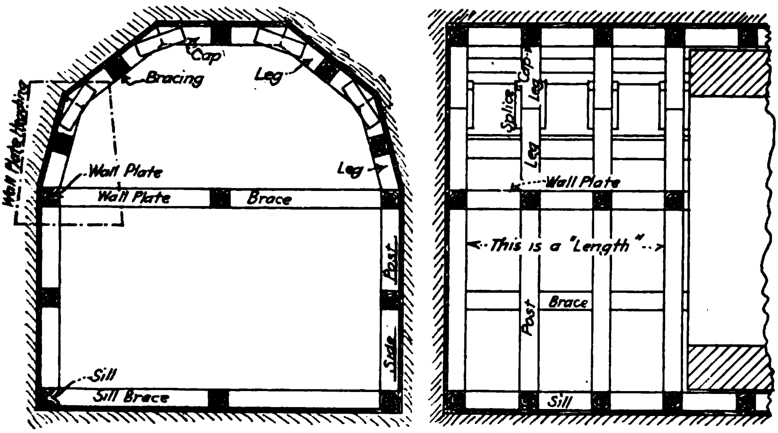


FIG. 3.—The American system of tunnel timbering.

square sawn lumber. They may be made of round timbers just as readily if these are more convenient to obtain, as in some foreign countries. Of late years it has become common to use steel I-beams for these segments with several important advantages accruing. A common procedure with the American system is to drive a pair of "wall-plate headings" in which the wall plate timbers (see Fig. 3) and the legs of the arch bents can be set as the first stage. These headings are timbered as described before. The first legs are set in these headings and wedged into

place against the sides of the heading. Then other headings are driven to take next leg above and finally the cap is set in a last heading. Headings may be driven next below the wall plates in which the sills are laid along the floor and the sideposts set to underpin the wall plates. We now have the roof and sides held on timbers with a core of earth remaining inside the timber. Cross headings may be driven from side to side at the bottom in which the sill braces are set and the bottom secured and finally whatever core of earth remains is removed under cover of the completed timbering. The exact sequence of these operations may

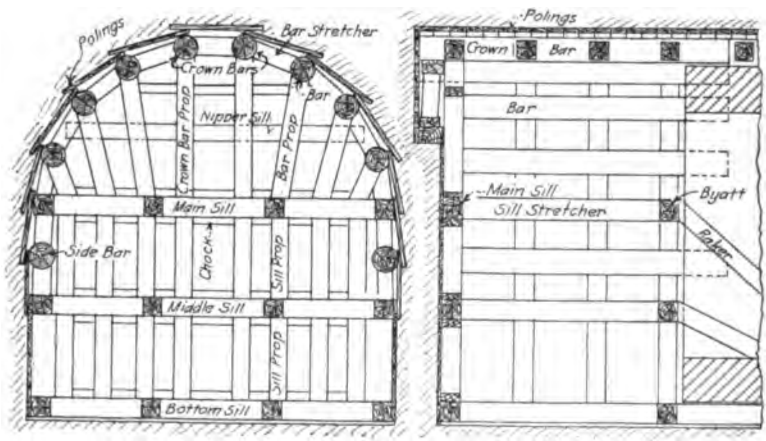


FIG. 4.—The English system of tunnel timbering.

be a matter of choice and may depend on the nature of the ground, which may not be uniform throughout the cross-section. For example the bottom sill heading may be driven first. No matter what the sequence is the process consists of opening the cross-section up, a bit at a time, by means of headings which are of small cross-section, and by interconnecting these primary headings by secondary excavations also of small individual cross-section until the main carrying timbers, closely sheathed, are in place.

22. English System.—Figure 4 shows the timbering of the English system. The bars are shown as of round timber, but they may equally well be made of square sticks. In modern times they are often made of steel I-beams which take less room,

and which are of more uniform strength and not liable to take fire or decay. With this system the first heading is almost invariably the "crown-bar heading." This is a heading which takes the two topmost bars, called the crown bars. The rear ends of these rest on the completed lining, the centers of which may be left in place to help carry the load in case the arch is considered too new to have developed its full strength. The front ends of these bars are held by short props which stand on a short

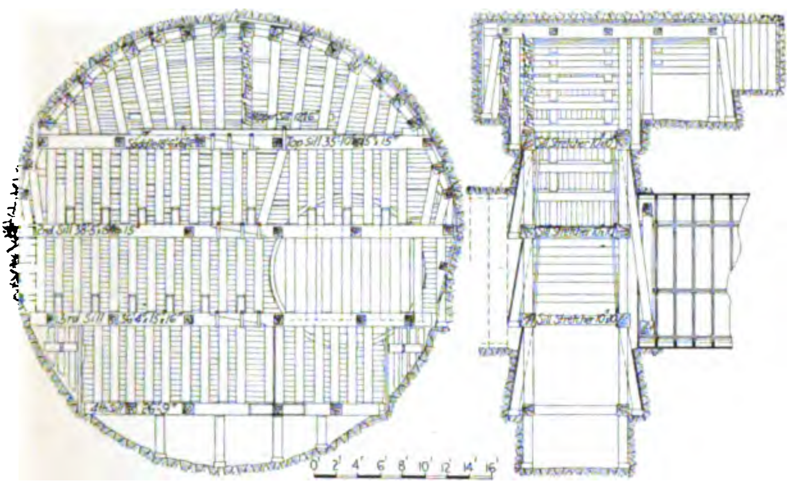


Fig. 5.—English timbering in clay for a tunnel 36 feet in diameter. City and South London Railway (E-10).

sill called a "leading nipper sill" (not shown in Fig. 4.) across the front end of the heading. To get these long bars into place through the narrow confines of the heading is quite a work of art and it is extraordinary the skill with which experienced men do this, as well as their other work. The two crown bars in place, a widening out is made on each side and when completed the next bar on each side of the crown bars is set in place, rear ends on the arch of the lining and the leading ends propped from another short leading nipper sill. The same is done for the next side bar. When the last bars are in place, the main sill is set across the front end of the length and all the bars are propped from the main sill. Owing to its massive section and its length it is usual to have the main sill in two sections, connected by a carefully

made scarf joint and clamped together with iron bands and splice plates. The whole of the top of the section is now secured and the remainder of the section is taken out by headings or drifts either on the center line or on the sides down to the level of the middle sill and so on down to the bottom. The number of sills depends on the size of the cross-section of the tunnel.

Figure 5 shows an actual example of timbering used in swelling clay for a circular excavation, 36 feet in diameter.

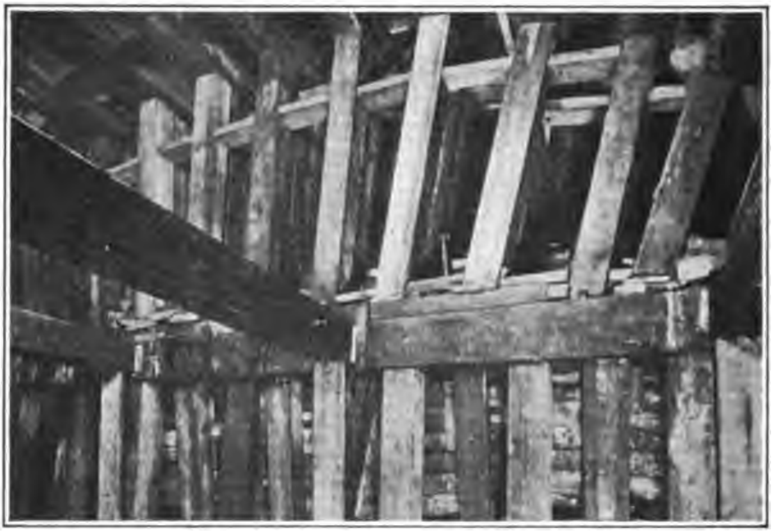


Fig. 6.—English timbering, showing bars, props, sill and stretchers. City and South London Railway (E-10).

Figure 6 is a photograph for a similar tunnel.

23. Principle of Operation.—The procedure in the main will be the same, whichever system of timbering is used. That is to say, it will consist of taking out a heading or headings along the line of the tunnel followed by further excavations connecting these headings within the area of the cross-section of the tunnel, timbering and supporting these excavations as they are made until at last the entire cross-section of the tunnel for a certain length has been made. The final timbering of the cross-section must have been in mind from the start, so that each piece of excavation which is done and each piece of timber that is put in

shall have its place and perform its function in the completed work. In any system it is essential to have plenty of longitudinal stiffeners and strength as collapse may come from the longitudinal thrust at the face, just as well as from the earth thrust normal to the tunnel cross-section. The longitudinal bracing is apt to be neglected and the engineer should see that this is not done. The entire workmanship must be of the highest class, all timbers which bear against one another must do so perfectly, everything must be wedged and spiked tight so that up to the breaking point it cannot budge. All voids outside timbers must be packed tight. Spaces in the poling which admit flowing ground must be packed with hay or straw or pugged clay or must be grouted up. In fact, the whole thing must be as tight as a drum. The timbers must be disposed to close together and get tighter the greater the pressure upon them. Particular care must be taken to ensure that no settlement takes place. It does not matter how well the roof timbering may have been done if settlement and especially unequal settlement occurs. The great principle is never to take too big a bite and to hold firm what you have got. Never let any movement start. Once you get a run on your hands you are up against a serious thing. Work to a regular plan in which each piece of timber does some particular work and where all main timbers have the same stress as far as may be and one which is within the safe stress of that kind of timber. It is usually better not to use the harder timbers for polings and main carrying members. Such wood is apt to give way without warning. What is wanted is something which will bend and give warning long before it will give way. When such warning is given put in special reinforcing timbers. Hardwood should be used for wedges and it is often advisable to use steel plates on the tops of posts and to use steel wedges for tightening up between caps and posts. The effort should be toward a general distribution of pressure and not toward a concentration at one point.

24. Timber Used.—It will be realized that the quantity of timber used is large, when the tunnel is large and the ground bad. Even that used for blocking, packing and wedging is enormous, and cases are plentiful where the timber used for these purposes comes to about the same volume as that of the main carrying members. Drinker (p. 626) gives the following table which illustrates this well.

TABLE I.—QUANTITY OF TIMBER USED IN TUNNELING BY MINING OPERATIONS IN VARIOUS GROUND

(From Drinker)

Character of rock	Timber used in cubic feet per 100 cu. ft. of ground excavated		
	Minimum	Maximum	Mean
Firm and self-supporting	1.3	5.5	4.0
Firm	5.9	8.5	7.0
Liable to fall	11.2	21.8	16.0
Soft ground	22.2	26.2	25.0
Pebbly ground	34.2	38.2	36.0
Running ground	48.3	56.8	53.0

If we take the figures given here as the mean and suppose a tunnel having a cross-sectional area of 625 sq. ft., equivalent to a circle of 28 ft. diameter, then for each mile of such a tunnel the quantities of timber and its cost at an assumed price of $50.00 per thousand feet B. M. for the various kinds of ground listed will be as shown in Table II.

TABLE II.—TUNNEL OF CROSS-SECTION 625 SQ. FT., ONE MILE LONG. QUANTITY AND COST OF TIMBER AT $50.00 PER M. B. M. FOR VARIOUS KINDS OF GROUND

Character of rock	Timber required per mile of tunnel		Cost of timber at $50.00 per M. B. M.
	Cu. ft.	M. B. M.	
Firm and self-sustaining	125,000	1,500	$ 75,000.00
Firm	218,750	2,625	131,250.00
Liable to fall	500,000	6,000	300,000.00
Soft ground	781,000	9,375	468,000.00
Pebbly ground	1,125,000	13,500	675,000.00
Running ground	1,656,250	19,875	993,750.00

This table shows how expensive a matter the very timber itself is and it is apparent that anything which reduces the quantity of timber required may save a large item of expense.

25. Timbering Cumbersome and Expensive.—With a tunnel

of ordinary railroad section, in very bad ground each length becomes such a mass of timber, all of which has a temporary value only, that it is a difficult matter for the men to get about and moreover the danger of collapse in really bad ground is never absent. The work must be done in stages, first a length of excavation, then a length of lining and so on. The length must be of some appreciable extent and the weight on a length may be too great for the timbers to withstand. Then either collapse occurs, or, if caught in time, still further timbers must be put in to hold it and thus the work of putting in the lining may be complicated and hampered still further.

26. Shield and Compressed Air Reduce Timbering.—It was to overcome these troubles, to some degree at any rate, that first the shield and then the use of compressed air were invented, as will be seen in the Chapter on History, the shield by Brunel and the use of compressed air by Cochrane.

27. Purpose of Shield.—The idea underlying the shield is that the process of setting forward the excavation and of building the lining should be split up into much smaller steps so that the two operations should be made more concurrent or simultaneous. The shield, consisting of a stiff metal envelope covering the cross-section of the tunnel as the cap of a telescope covers that instrument, serves to withstand the earth pressures while the short length of lining is built within its protection. The first shield used by Brunel—in the Thames tunnel—was provided with a complicated system of breasting boards which could be held against the face of earth by means of screws, while the segmental shield itself could be moved forward into the ground by means of screw jacks abutting against the finished lining. The theory was, that by a mechanism capable of forward movement along the course of the tunnel and provided with means of withstanding the earth pressure at the face as well as against the earth pressures acting at right angles to the periphery of the tunnel, all or most of the expensive timbering employed by the mining methods hitherto used might be eliminated. As a matter of fact, Brunel's ideas were rather in advance of the mechanical arts of his day and his shield in practice was so complicated and difficult to handle that the result was that a great period of time and an enormous amount of money was required to see his tunnel completed. This is so even when allowing for the really gigantic cross-section of the tunnel which he built and

which well might give the stoutest heart pause even at the present day. (See Fig. 20.)

28. Purpose of Simplified Shield.—Of recent years, the tendency has been toward the simplification of the mechanism of the shield so that it forms now, as it were, a framework, a form and an abutment against which the miner can dispose his timber and within the protection of which the permanent lining can be built. In other words, the modern shield—except in the more fluid forms of homogeneous ground such as mud and silt—does not displace the miner and his timber entirely but merely is a powerful adjunct to him, enabling progress to be made in shorter steps and with the expenditure of much less time and much less timber. This will be understood better later on in this book where the methods of tunnel construction by shield are detailed.

29. Purpose of Compressed Air.—The other great invention, namely Cochrane's, whereby air under a pressure greater than that of the natural atmosphere is introduced into a tunnel, has the same object in view, namely to make simpler and quicker the work of the miner in waterbearing ground. Cochrane knew that every foot in height of water exerts a pressure of 0.434 lb. per square inch and that therefore, if he could introduce into a tunnel air under a pressure above normal corresponding to the number of feet of head of water acting upon that tunnel he would be able to hold back the water from its tendency to flow into the excavation, so that the method of excavation used could be changed from that required in wet ground (under that head) to that required in dry ground. The invention was made at the time that Brunel was struggling with the constant inrushes of water into the Thames Tunnel and there is little doubt that this invention was inspired by Brunel's work. It is said that Dr. Colladon suggested using Cochrane's patented idea to Brunel. Be that as it may, Brunel did not use it and it was not until the year 1879 that compressed air was used in tunnel work, simultaneously at Antwerp and at New York.

30. Effect of Compressed Air.—Although the application of compressed air to a wet tunnel simplifies greatly in most cases the difficulty and danger of the work it must be made quite clear at the outset that it does not convert a difficult problem into one of childish simplicity. The head of water at the top of the tunnel must be less than that at the bottom by an amount corresponding to the vertical dimension of the tunnel. The compressed air,

on the other hand, which is introduced into the tunnel for the purpose of holding back the water can have but one pressure. If the pressure of the air introduced is equal to the pressure of the water at the top of the tunnel, the top will be dry, but the rest of the tunnel will be wet, and the degree of wetness will increase the further toward the bottom we get. If the air introduced has a pressure equal to the head of water at the horizontal axis of the tunnel, then all that part above the horizontal axis will be dry and all that below will be wet. If the air pressure introduced is equal to the head of water at the bottom of the tunnel then the whole tunnel will be dry.

31. Unbalanced Air Pressure.—It may be said, therefore, why not always introduce the air at such pressure that the head of water will be balanced at the bottom of the tunnel and thus do our work in the dry? The answer is that we now have an excess of air pressure at all parts of the tunnel cross-section above the bottom and that this excess increases from bottom to top; therefore the excess pressure of the air is at its maximum at the top of the tunnel. Owing to this excess pressure there is a constant escape of air through the ground which may form constantly enlarging channels in the ground and may in time lead to forming a direct passage from the tunnel to the bed of the overlying waterway. The water alone cannot prevent the air, which has a pressure greater than that of the column of water, from escaping. The air, therefore, will rush out like a geyser at a speed greater than can be supplied to the tunnel, thus leading to a fall of the air pressure below that even of the water pressure at the top of the tunnel, so that no longer is there any restraint upon the flow of water. The tunnel then becomes flooded with water and earth. In fact, no matter what air pressure is kept in the tunnel, there is a state of unstable equilibrium. The more "open" the ground and the greater the vertical dimension of the tunnel the more accentuated the degree of instability. In dense, homogeneous and heavy ground such as clay there may be a considerable lack of balance without much fear of a "blow" or a run. In such ground, however, the value of compressed air is less, than in the open, loose, light and flowing grounds which are the miner's great difficulty and dread and where he needs the assistance of the compressed air to the greatest degree.

32. Example.—To illustrate the effect of vertical dimension on the lack of equilibrium we may imagine five tunnels each with

its top 50 ft. below the water so that the pressure of the water at the top is 21.7 lb. per square inch. The tunnels are 10, 20, 30, 40 and 50 ft. in vertical dimension, respectively. The conditions of pressure will then be as shown in Table III.

TABLE III.—EXTERNAL WATER PRESSURE ON TUNNELS OF VARIOUS SIZES

Vertical dimension of tunnel in feet	Hydrostatic head in pounds per square inch			Percentage of difference
	Top	Bottom	Difference	
10	21.70	26.04	4.34	20
20	21.70	30.38	8.68	40
30	21.70	34.72	13.02	60
40	21.70	39.06	17.36	80
50	21.70	43.40	21.70	100

It is plain that, in any given kind of ground, it will be much safer to carry an air pressure which will balance the hydrostatic head at the bottom, if the tunnel is only 10 ft. in vertical dimension and where there is only 20 per cent difference in head between the top and the bottom, than in a 50-ft. tunnel where the difference is 100 per cent.

33. Differential Air Pressure Shield.—It is this difficulty which has led to the various attempts to introduce a differential air pressure at the face of a large tunnel, by which is meant attempts to devise apparatus in the shield whereby the air pressure in the upper part of the shield would be less than at the middle level and this again less than at the bottom. No successful application of this idea has yet been made and indeed it would appear impossible, because in open ground, in which such a device would have its use, the higher pressure air would inevitably short circuit itself into the lower pressure levels and thus defeat the object sought.

34. Hydrostatic Pressure.—In the preceding discussion the air pressure required to balance the external hydrostatic pressure has been assumed to be equal to the head of water. This is true only in general terms. Actually there is a loss of head due to the resistance to percolation through the ground. This resistance is least in open ground, such as gravel or sand, and in such materials the air pressure needed to keep the ground dry at any given depth is approximately equal to the head of water. In

clay the resistance to percolation is great, in fact, it may be so great as to oppose percolation completely. Under this condition it is possible to tunnel under a waterway without encountering water. On the other hand, if the ground is supersaturated with water, which may occur in mud or silt, the ground may act as a fluid of a density greater than that of water, and in this case, the air pressure required to keep the ground from moving may approach that of the combined head of water and ground. The exact pressure needed to dry the ground in any given case can be ascertained only in the tunnel itself.

35. Conclusion.—This bare outline may give an idea of the difficulties which confront the miner called upon to drive a tunnel through soft waterbearing ground; how the work is done by patient skill and the expenditure of great quantities of timber scientifically placed to withstand the great forces at play; how the shield was invented to overcome some of these difficulties and proved such a wholly new and valuable an aid as to become a necessity in certain cases and a saver of time and money in many more, and how the invention of the application of compressed air to tunnel work still further simplified the problem when water was present. The next chapter gives a summarized account of the dates of these inventions, how first the shield alone was used, then the shield in combination with compressed air and how these methods have led to an enormous increase in the engineer's power to build, comparatively cheaply and comparatively safely, tunnels which without their use might have been either prohibitively expensive or perhaps impossible.

CHAPTER IV

HISTORY

1. Necessity of Method.—The need of underground thoroughfares where the difficulties of construction by the ordinary mining methods were too great, was the direct cause of the invention of the shield method of tunneling. The possibilities of the method were indicated when, by the use of the first shield ever built, a tunnel was driven where mining methods had failed.

2. Brunel and His Thames Tunnel.—This tunnel was constructed under the Thames by Marc Isambard Brunel. He, the son of a small farmer, was born in France in 1769, came to New York in 1792 and left there for England in 1799 where he stayed until his death in 1845. He conceived and patented in 1818 the first tunnel shield and used a shield for building the first tunnel under the Thames. The external cross-section of this tunnel was a rectangle with a height of 22 ft. 3 in. and a width of 37 ft. 6 in. Up to the present time only one shield driven tunnel (at Elm, Germany) has exceeded this tunnel in area. See Fig. 20. The work was commenced in 1825 and finished in 1843. The difficulties were stupendous. Twice the river broke into the works, once the shield was removed and rebuilt and for seven years the work was closed down for lack of money. Brunel and his son practically lived in the tunnel while the work was in progress and often they had to do their work from a boat floating in the tunnel. Brunel completed the task he had set out to do, but the incessant strain broke down his health and he died two years after the work was done.

3. Causes of Difficulties.—The difficulties encountered were due partly to the large size of the tunnel, partly to the new and untried appliances of complex design, almost ahead of the mechanical possibilities of the time, and partly to the fact that while Brunel had provided means of holding up the excavation, he had made no provisions for keeping out the water, although he must have known of the possibilities of compressed air which, it is stated, were pointed out to him by Dr. Colladon in 1828.

4. Principles of Brunel's Shield.—The details of Brunel's shield, which differed from those shown in his original shield patent (No. 4204) of 1818, have not been repeated, but the fundamental principles embodied in this patent form the basis of the modern shield. These principles include

(*a*) A mantle or envelope covering the whole periphery of the tunnel and forming a protection under which the work of excavation can be carried out and the lining erected without the necessity of internal timbering.

(*b*) An internal stiffening structure to prevent the collapse of the envelope, provided with horizontal platforms, where the tunnel was large enough, so that the work can be carried out conveniently at several stages, and with vertical partitions, so as to form several working chambers.

(*c*) A rear extension of the envelope, or tail, clear of any internal structure, overlapping the tunnel lining already erected, under cover of which the lining may be erected in short lengths.

(*d*) Hydraulic jacks for moving forward the shield.

Only in one principle does this shield differ from the present day shield, namely in being divided into a number of cells, which could move forward some distance independently of each other. In other words, not only the internal structure was so divided but also the envelope which formed an integral part of the separate cells.

5. Early Patents.—No other shield tunneling was carried out until 1869, but the interest in tunnel shields was kept alive as evidenced by a number of patents taken out prior to that time with the view of improving on Brunel's original patent. Amongst these is one taken out by S. Dunn in 1849. The design described in this patent resembles that of the present day shield in showing it made all in one piece. A patent granted R. Morton in 1866 is of interest by the fact that in this the word "shield" is used for the first time in describing the appliance. Prior to this the word "cell" or "cylinder" had always been used. In 1864 Peter W. Barlow patented a shield to be used with a circular cast iron lining which was to be grouted on the outside. He also obtained in 1869 a provisional patent which describes a shield having a vertical diaphragm. The first patent is of interest, because it probably formed the basis for the first tunnel shields constructed since that of Brunel. Shields were built simultane-

ously in the year 1869 in America and England, but independently of each other.

6. Greathead and the Tower Subway.—In 1869 Barlow had promoted the construction of the Tower Subway, a small tunnel for foot passengers under the Thames River at London. No contractor would undertake the work. Brunel's difficulties were still fresh in men's minds. Finally James Henry Greathead, who was then 26 years old and one of Barlow's assistants, offered to carry out the work as Barlow's contractor. The offer was accepted. Greathead designed the shield, superintended the construction of the tunnel and finished the work within the year 1869. The tunnel was 7 ft. 1¾ in. in external diameter and 1,350 ft. long. It was built in non-waterbearing clay throughout. From that time until his death in 1896 Greathead's life work was shield tunneling and he was connected with the design or the construction of nearly all shield driven tunnels built during that period.

7. Beach and the Broadway Tunnel.—While the Tower Subway was being built in London a tunnel was being constructed by the shield method under Broadway in New York City. The shield for this tunnel was designed and built in 1869 by A. E. Beach, then editor of the Scientific American. The shield had a diameter of 8 ft. and was the first in which hydraulic jacks were used for driving forward the shield. That of the Tower Subway was propelled by screw jacks. The tunnel was intended for a "pneumatic railway" in which the cars were to be moved by compressed air. The shield was driven under Broadway from Warren Street to Murray Street through dry sandy ground and the tunnel was opened to the public on Feb. 26, 1870. In 1915, when the new rapid transit lines were built under Broadway, the shield was found partly intact at Murray Street. Beach shields were used in tunnels at Cincinnati, Ohio, and Cleveland, Ohio, the following years. At the latter place the shield ran into soft and waterbearing ground in 1872 and the method was abandoned.

8. Shields Used in Dry Ground.—While Brunel's shield was conceived originally and used as a means of tunneling through waterbearing ground, the Tower Subway and the Broadway Tunnel, in both of which the modern type of one-piece shield was used, were driven through dry ground. This was a great help in the development of the shield method, because it gave experi-

ence in the use of the shield before the necessity arose of coping with the additional problem of keeping out water.

9. Compressed Air in Engineering Work.—As previously stated, Brunel's attention was called to the possibilities of compressed air as a help to keep the water out of his tunnel, but he did not attempt to put it into practice. It is evident, however, that his difficulties inspired Admiral Sir Thomas Cochrane, Lord Dundonald, to conceive a method of using compressed air in tunneling and shaft sinking. In the year 1830 Cochrane took out a patent (No. 6018) for an apparatus, which is in fact the modern air lock. The first time compressed air and the air lock were used in engineering work was in 1839 when a French engineer Triger sank an iron lined coal pit at Chalons, France. The word "air lock" was not used until 1851, when J. Hughes used it in describing the work of sinking caissons for the Rochester bridge, England.

10. Compressed Air Applied to Tunneling.—The honor of first applying compressed air to tunnel work is divided between New York and Antwerp. At the latter place Mr. Hersent used it in 1879 for driving a small tunnel lined with cast iron in connection with some dock work he was carrying out. The tunnel was rectangular in shape, although each side had an outward curve. It was 5 ft. high and 4 ft. wide. In the same year DeWitt Clinton Haskin started to build a tunnel on a much larger scale, involving the crossing of the Hudson River between Fifteenth Street, Jersey City and Morton Street, New York City. There were to be two tunnels, each 18 ft. high and 16 ft. wide and lined with brickwork. The work was carried out principally from the New Jersey shaft and compressed air was used. In 1880 a serious accident occurred, but the work was continued until 1882 when Haskin's capital was exhausted and the work suspended. By that time 1,540 ft. of the North tunnel had been completed from the Jersey City shaft and 74 ft. from the New York shaft, and of the South tunnel 600 ft. had been driven from the New Jersey shaft. Later—in 1889—this work was revived by an English company with Baker and Greathead as the consulting engineers. The contractor was S. Pearson and Son, with E. W. Moir in charge. A shield was built in the North tunnel and 2,000 ft. of tunnel was driven by means of this shield and lined with cast iron with an external diameter of 19 ft. 6 in. In 1891 the work was again stopped by lack of capital. Finally, in

1902, the work was again started under the direction of Charles M. Jacobs, and on March 11, 1904, the North tunnel was holed through. The completion of the South tunnel followed soon after and the two tunnels now form part of the Hudson and Manhattan Railroad system.

11. Tunneling with Shield and Compressed Air.—The first use of compressed air in conjunction with shield tunneling occurred in 1886 on the construction of the original portion of the City and South London Railway, then called the London and Southwark Subway. It involved the construction of more than 6 miles of tunnel. The external diameter of the cast iron lining varied. On one portion it was 10 ft. 10¾ in. and on the remainder it was 11 ft. 3 in. For the greater part of the length the work was in clay impervious to water, but short stretches of open waterbearing ground were met. Here for the first time compressed air was used in conjunction with a shield. The shields used were of the Greathead type and were designed by him in his capacity as the chief engineer of the work.

12. Greathead's Grouting Pan.—In connection with this work Greathead had designed and patented (No. 5221) his grouting machine, used to force lime or cement grout outside of the tunnel lining and thus fill the voids left by the tail of the shield. This machine has survived practically in its original form to this day and next to the shield and compressed air it is the most useful tool the tunnel man has.

13. Shields for Compressed Air Work.—The shields used on the City and South London Railway tunnels were made for dry ground tunneling and the use of them in waterbearing ground in connection with compressed air was incidental. Shields purposely constructed for compressed air work were first used in 1888, simultaneously in England and in America. The English tunnel was the Vyrnwy Aqueduct tunnel under the River Mersey near Liverpool. The external diameter of the tunnel was 10 ft. The ground was known to be waterbearing and a shield designed with this condition in view was started, but did not prove successful. After consultation with Greathead and Baker it was changed, therefore, so as to form a water trap. This was the first shield of this type and it performed its work successfully. The other shield specially designed for waterbearing ground and built the same year was for the Sarnia tunnel, which carries the trains of the Grand Trunk Railroad under the St. Clair River

between the United States and Canada. This tunnel had an outside diameter of 21 ft. and was the largest shield tunnel attempted up to that time, except Brunel's. The shield was designed by J. Hobson and was successfully carried through the soft waterbearing clay under the St. Clair River.

14. Method Developed.—The success of the work on the Sarnia tunnel gave an undoubted impetus to the new method as it showed the possibility of rapid and successful tunneling where ordinary mining methods would have been hazardous or impossible. This work was closely followed by the resumption of the construction of the Hudson tunnel in 1889 (see par. **10**) by the shield method and in 1892 by the work on the Blackwall tunnel under the Thames. This latter tunnel had an outside diameter of 27 ft. and was driven through open and difficult waterbearing ground without undue delays. In its completion Brunel's ideal may be said to have been realized. From now on shield driven tunnels were built in rapid succession for all purposes, of all sizes and through any kind of ground.

15. Value and Limitations of Shield.—Naturally during its infancy and adolescence the tunnel shield has sometimes been looked upon as a panacea for all the ills of tunnel building. That stage is about passed. The present tendency is to accept the shield for what it really is, namely an adjunct to and not a substitute for mining methods. It offers as such important advantages in diminishing the timbering otherwise necessary, in safeguarding the work, in speeding the progress and in extending the field of tunneling. With this in view the design is made without unnecessary and complicated appliances but as strong, stiff and powerful as the conditions will permit. After all, the shield alone does not build the tunnel. Successful tunnel construction is achieved only by incessant care and workmanlike execution.

16. Equipment of Shield.—We have followed the development of the tunnel shield from its inception until a workmanlike machine was developed, capable of driving tunnels—if necessary with the assistance of compressed air—through any kind of ground. Some main parts of the equipment of the shield may be mentioned briefly.

(*a*) *Shield Jacks.*—The shields for Brunel's tunnel and for the Tower Subway were propelled by screw jacks. The first shield provided with hydraulic jacks was that for the Broadway tunnel

in New York in 1869. In the early shields the pressure was supplied by a hand pump mounted on the shield and the capacity was 2,000 lb. per square inch or less. On the Sarnia and later tunnels the pressure was supplied by mechanically driven pumps. On the Hudson tunnel shield of 1889 the pressure was 4,000 lb. per square inch and on later shields it has ranged from 5,000 to 6,000 lb. per square inch.

(*b*) *Segment Erector.*—On the Sarnia tunnel (1888) the weight of the cast iron segments and the size of the tunnel necessitated mechanical means for manipulating the segments during the erection. A mechanical erector, therefore, was attached to the shield and worked by hand. On the Hudson tunnel (1889) a hydraulic erector was provided mounted on a platform behind the shield. The first shield on which a hydraulic erector was mounted directly on the shield was that of the Blackwall tunnel (1892), and two erectors were provided on this shield.

(*c*) *Face Jacks.*—The first shield furnished with face jacks for the support of the face breasting during the forward movement of the shield was that of a station tunnel on the Waterloo and City Railway in 1895. Since then face jacks have been found a useful adjunct on many shields.

(*d*) *Hood.*—The hood is a forward extension of the upper part of the shield envelope. It was first applied as a protection for the men working in front of the shield on the shield of the Siphon de la Concorde in 1892, and has since been used for the same purpose on several shields driven through open ground. In the year 1892, Dalrymple Hay used the hood on the Waterloo and City Railway in conjunction with "clay pockets" to dispense with the use of circumferential timbering in front of the shield.

(*e*) *Vizor.*—A more pronounced forward extension of the shield envelope has been used on several French and German shields, the purpose being to make the front plane of the shield conform approximately to the natural slope of the ground so as to avoid the necessity of timbering the face. An example of this is afforded by the shield for the Spree tunnel (1895).

17. Mechanical Excavators.—The introduction of the shield did not remove the necessity of excavating by hand except in specific instances, as for example when tunneling through Hudson River silt, in which case the shield may be driven forward into the ground without excavating the material. In most other kinds of ground the material in front of the shield must be

excavated before the shield can advance. Attempts have been made to do this mechanically and several machines have been devised. One of the earliest and most successful is the Price Excavator, first used on the Central London Railway in 1897 and since then many miles of tube railways in London have been excavated by means of this machine. It is best suited for clay, but it has also been used through open waterbearing ground. An American machine, originally devised by Charles Bonnet, was used first in the year 1914 on some sewer construction in Detroit, Mich., without a shield.

18. Roof Shield.—A variation of the regular tunnel shield is presented by the "roof shield." This type of shield resembles in principle the regular type, except that it does not enclose the complete tunnel but only the arch. The first attempt to use a roof shield was made in Baltimore in the year 1892, but owing to insufficient strength the shield distorted and was abandoned. The first successful use of a roof shield was made in Paris in 1895 on the construction of the Collecteur de Clichy extra muros. The span of this shield was 23 ft. 9 in. The shield was designed by Chagnaud, the contractor on the work, and the construction of the tunnel was carried out under the direction of Reynald Legouez.

19. Cast Iron Lining.—In his patent specifications of 1818 Brunel shows a circular tunnel and states that he prefers cast iron as a lining material. While he did not use it himself, circular cast iron tunnel lining has been in almost universal use until recent years. It has the advantage of being capable of withstanding the jack thrust and earth pressures immediately after being erected.

20. Masonry Lining.—With the first roof shield, masonry lining was again introduced. In order to avoid the masonry being exposed to the thrust of the shield jacks these were made to bear on the form work instead of on the lining. This method has been used in some later cases. When the Tremont Street tunnel in Boston was being constructed in the year 1897 with a roof shield, Carson introduced longitudinal thrust bars in the concrete lining. In some cases, however, the jack pressure has been taken up directly by the freshly deposited concrete. The first instance when this method was used was on the Siphon de l'Oise near Paris in 1897. The tunnel was circular with an external diameter of 8 ft. 3 in. and was driven with a regular

shield. The method was not entirely successful here, but it has been developed further by a German firm, Hallinger & Co., with apparent success.

21. Block Lining.—Blocks of masonry laid without mortar have also been used for tunnel lining. One of the earliest instances is that of some sewer tunnels in Melbourne, Australia, (1893) where bluestone or precast concrete blocks were used in shield driven tunnels, ranging in size from 5 ft. 9 in. to 11 ft. 6 in. One of the most notable examples of the use of precast concrete blocks for lining a shield driven tunnel is that of the Cleveland New West Side Intake Tunnel (1915). This tunnel is over 16,000 feet long in clay and is lined throughout with precast concrete blocks.

22. Wood Lining.—In several instances shield driven tunnels have been provided with a primary lining of wood, supplemented with an internal lining of masonry. The advantage of this construction is that the wood lining may be immediately self-supporting and capable of carrying the thrust of the shield jacks. One of the first examples of wood lining is also that of the sewer tunnels in Melbourne (1893) where shield driven tunnels ranging from 9 ft. 9 in. to 10 ft. 6 in. in diameter were lined primarily with wood. In 1915 the Dorchester tunnel, Boston, was constructed with a primary lining of wood. This tunnel has an external diameter of 24 ft. 2 in. and is the largest tunnel so far built with wood lining.

23. Compressed Air Work.—Compressed air has proved itself a powerful help in the construction of tunnels, not only in conjunction with the shield method, but also where tunneling can be carried out without the use of a shield. The most important example of tunneling in compressed air without shield is perhaps afforded by the Cleveland East Side Intake Tunnel (1898), 26,000 ft. of brick lined tunnel with an external diameter of 11 ft. 2 in. In the early days work in compressed air was fraught with danger. E. W. Moir has stated (Journal of the Society of Arts, May 15, 1896) that before his time (1889) on the Hudson tunnel men had been dying at the rate of about 25 per cent per annum. He introduced there the "Hospital Lock" which since has been used universally on compressed air work and which has relieved much suffering. As conditions became better understood, sufficient fresh air was supplied to the working chamber, the time of locking out was regulated and proper sanitary rules

were enforced, removing many of the dangers of work in compressed air. The safety of the men working in compressed air in case of flooding of the tunnel was also better secured by a number of safety appliances, among which may be mentioned the safety screen, originally proposed by Van der Veyde in 1880, and first applied in the Blackwall tunnel (1892).

24. Shield Driven Tunnels.—It has been shown that while shield tunneling started as early as 1825, it was not until 1886, that it was carried out in earnest. Since that time, however, it has been carried out almost continuously in many countries. In the following pages—arranged chronologically for each country—a short description is given of each shield driven tunnel of which we have been able to find records. Each tunnel is given a serial number, and this number is used for reference in the succeeding chapters, where mention is made of that tunnel. In this list, names as Drinker, Simms, Legouez, Copperthwaite, Dolezalek refer to books by these authors. The full titles of these books are given in the bibliography at the end of this book.

America

A-1. Broadway Subway. 1869–1870.

Under Broadway, New York City, between Warren Street and Murray Street. Length 294 ft. External diameter about 9 ft. 4 in., internal diameter 8 ft. Brick lining. Shield designed by A. E. Beach. Top of tunnel 21 ft. below street bevel. Loose sandy ground. Built for a pneumatic railroad. Abandoned.

Ref. *Scientific American*, March 5, 1870.

A-2. Cincinnati Sewer. 1871–1872.

From Abigail Street under Sycamore Street and Court Street to Broadway, Cincinnati, O. Internal diameter 8 ft. Beach shield. Brick lining.

A-3. Cleveland Water Intake. 1871–1872.

Under Lake Erie. Beach type shield tried but abandoned after being used for a length of 140 ft. on account of the fluid character of the ground. External diameter 6 ft. Brick lining.

A-4. 12th Street Intake, Chicago. 1887–1892.

Under Lake Michigan. Internal diameter 8 ft. Shield tried but soon abandoned.

A-5. Sarnia. 1888–1890.

Single track railroad tunnel under the St. Clair River, forming the boundary between the Province of Ontario, Canada and the State of Michigan, U. S. A. Length 6,170 ft. External diameter 21 ft.; internal diameter 19 ft. 10 in. Cast iron lining. Ground, soft clay. Top of tunnel 55 ft. below water level and 20 ft. below river bed. Average progress 228 ft. per month. Air pressure 28 lb. per square inch.

Ref. *Eng. News*, Oct. 4, Nov. 8, Nov. 22, Dec. 6, 1890. Legouez, 1897, pp. 122–156. Copperthwaite, 1906, pp. 172–180.

A-6. Hudson. 1889–1905.

Under the Hudson River between 15th Street, Jersey City and Morton Street, New York. Commenced in 1879 without shield but with compressed air. Suspended in 1882. Recommenced in 1889 by the shield method. Suspended again in 1891. Restarted in 1902 and completed in 1905. This tunnel now forms the North tube of the up-town lines of the Hudson & Manhattan Railroad. Total length driven by shield 3,507 ft. Cast iron lining, external diameter 19 ft. 6 in.; internal diameter 18 ft. 2 in. Ground, silt, sand, rock; mostly silt.

Ref. Drinker, pp. 961–976; Legouez, 1897, pp. 89–121. Copperthwaite, 1906, pp. 159–172. *Eng. News*, March 15, 1890; April 12, 1890, April 26, 1890; July 19, 1890; Nov. 15, 1890.

A-7. Baltimore Belt Line. 1891–1892.

Railroad tunnel under Howard Street, Baltimore. Roof shield of 30 ft. 8 in. span used for arch and two rectangular shields 9 ft. high by 8 ft. wide for bottom headings. Roof shield distorted soon after being started and shields removed. Ground was sandy clay with water.

Ref. *Eng. News*, Jan. 9, 1892.

A-8. Ravenswood. 1892–1894.

Tunnel for gas mains under the East River, New York City, between 71st Street, Manhattan, and Long Island City. Top of tunnel 110 ft. below high water and minimum depth to river bed 41 ft. Shield used for short stretches only through seams of decomposed rock. Two shields used, one at the Manhattan end for a distance of 163 ft., and one at the Long Island end for a distance of 65 ft. These portions of the tunnel were lined with cast iron, external diameter 10 ft. 10 in.; internal diameter 10 ft. 2 in. Maximum air pressure 52 lb. per square inch.

Ref. *Proc. Boston Soc. C. E.*, April 17, 1895; *Eng. News*, July 11, 1895. Legouez, 1897, pp. 200–226. Copperthwaite, 1906, pp. 215–222.

A-9. Ripley. 1896–1898.

Tunnel for water supply at Ripley, N. Y., through a hill 700 feet long. Mostly done by mining methods but the last 60 ft. through quicksand were done by the shield method, under compressed air. Wood lining external diameter 4 ft. 10 in.

Ref. *Eng. News*, June 9, 1898.

A-10. Tremont Street. 1896–1897.

Double track railroad tunnel under Tremont Street, Boston, Mass. Length driven by roof shield 550 ft. Overall width of roof shield 29 ft. 4 in. Brick arch. Ground, clay and sand with boulders, loose sand and gravel. Average progress 9 ft. per working day.

Ref. Copperthwaite, 1906, p. 303 to p. 312.

A-11. Malden Bridge. 1898–1899.

Siphon tunnel for gas main under Mystic River at Malden Bridge, Charlestown, near Everett, Mass. Length 1,515 ft. Wood lining. External diameter 5 ft. 6 in. Carries a 54 in. pipe and space between pipe and wood is filled with concrete. Cost $50,000.00.

Ref. *Proc. Borton Soc. C. E.*, April 17, 1901. *Eng. News*, October 3, 1901.

A-12. 39th Street Sewer, Chicago. 1899–1902.

Main intercepting sewer tunnel in 39th Street, Chicago, from Lake Michigan to Butler Street. Length 9,563 ft. Wood lining with interior

brick lining. External diameter 24 ft. 9 in. Internal diameter 20 ft. Progress 9 ft. per working day. Average air pressure 9 lb. per square inch.

Ref. *Eng. News*, August 3, 1899; May 28, 1903. *Eng. Record*, January 19, 1901.

A-13. East Boston. 1900–1903.

Double track railroad tunnel under Boston Harbor from State Street to Lewis Street, East Boston, Mass. Length 4,350 ft. Roof shield. Overall width of shield 29 ft. Top of tunnel 68 ft. below H. W. and 22 ft.below bed of harbor. Concrete lining. Average progress 5 ft. per day. Ground mostly blue clay. Average air pressure 20 lb. per square inch.

Ref. Boston Transit Commission, *Annual report*, 1901, 1902. Copperthwaite, 1906, pp. 312–324. *Eng. News*, April 4, 1901; Jan. 23, 1902; June 4, 1903.

A-14. Mystic River. 1901.

Water pipe tunnel under Mystic River at Boston, Mass. Length 132 ft. Wood lining, external diameter 9 ft. 4 in. Ground, gravel, boulders and clay. Air pressure 24–29 lb. per square inch. Average progress 1.8 ft. per day. Cost $11,800.00.

Ref. *Eng. News*, Sept. 26, 1907.

A-15. Cleveland Intercepting Sewer. 1902–1912.

Sewer tunnel along the shore front of Lake Erie, Cleveland, O. First length of 1,100 ft. built in 1902, external diameter 16 ft. 6 in., internal diameter 13 ft. 6 in. Brick lining. Ground, plastic clay. Air pressure 7 lb. per square inch. Average progress 6 ft. per day. Last 6,800 ft. with an internal diameter of 12 ft. 3 in. was built at an average progress of 9 ft. per day and at a cost of $35.00 per linear foot. Total length 24,500 ft., mostly with wood lining and interior brick lining.

Ref. *Eng. News*, March 28, 1912.

A-16. Battery. 1903–1906.

Two single track railroad tunnels from Battery Park, Manhattan under the East River, to Joralemon Street, Brooklyn, New York. Each tunnel is 6,766 ft. long, of which length about 2,540 ft. from the Manhattan side to nearly halfway across the river was in rock and driven without shield. Total length of shield driven single track tunnel 8,450 ft. Cast iron lining, external diameter 16 ft. 8½ in. Four types of lining were used as follows:

Type	Internal diameter, feet	Thickness of skin, inches	Weight per linear foot, lb.
Light	15.54	1.125	3,992
Heavy	15.46	1.125	4,545
Special extra heavy	15.46	1.125	5,133
Extra heavy	15.46	2.000	5,593

The light type was used through rock. The heavy type was used in soft ground under the river and on the Brooklyn shore below high water. The special extra heavy type was used from the Brooklyn bulkhead line for a

distance of about 900 ft. under the river. The extra heavy lining was used for short lengths under bulkheads, at end of rock portions and similar places. Tunnels settled at certain places and were supported on piles. Ground mostly sandy. Top of tunnel 75 ft. below H. W. and minimum cover 16 ft. Maximum air pressure 42 lb. per square inch. Average 35 lb. per square inch.

Ref: Brooklyn Engineer's Club, *Paper* 80, Feb. 13, 1908. *Eng. News*, June 27, 1907. *Eng. Record*, March 5, March 12, 1904; Sept. 9, 1905; June 2, 1906; March 2, 1907; July 20, 1907.

A-17. Hudson & Manhattan. 1902–1908.

In addition to the Hudson Tunnel (No. A-6) the Hudson & Manhattan Railroad Company's shield driven tunnels consist of one single track tunnel parallel to and south of No. A-6 across the Hudson River from 15th Street, Jersey City to Morton Street, New York; two single track tunnels from Morton Street to 12th Street, 6th Avenue, New York; two single track tunnels across the Hudson River between Pennsylvania Railroad Station, Jersey City and Church Street, New York and of two single track tunnels along certain portions of the New Jersey shore between Pennsylvania Station, Jersey City and the Hoboken, N. J. Terminal. Total length 35,317 ft. of single track shield driven tunnel. External diameter 16 ft. 7 in. Internal diameter 15 ft. 3 in. Cast iron lining. Top of tunnel 75 ft. below high water. Minimum cover 10 ft. Material, sand, gravel, rock, mixed face and silt. Average progress, up town 9.3 ft. per day. Downtown in silt almost 16 ft. per day. Average cost $300 per linear foot of single tunnel. Average air pressure 25 lb. per square inch.

Ref. *Proc. Inst. C. E.*, Vol. 181, pp. 169–257.

A-18. Pennsylvania Railroad North River.

Two single track railroad tunnels under the Hudson River from Weehawken, New Jersey, to 32nd Street, Manhattan. Shields started May 12, 1905; tunneling completed November 18, 1906. Length of shield driven tunnel, total 12,196 ft. Cast iron lining with interior concrete lining. Ext. dia. 23 ft.; internal diameter 19 ft. Top of tunnel 70 ft. below H. W. and 20 ft. below river bed. Rock, sand, gravel, mostly river silt. Average progress in silt, 14.42 ft. per day of 24 hours. Air pressure, average 26 lb.

Ref. *Trans. Am. Soc. C. E.*, vol. 68.

A-19. Pennsylvania Railroad East River.

Four single track railroad tunnels under the East River from 33rd and 34th Streets, Manhattan, to Van Alst Avenue, Long Island City. Total length of single track shield driven tunnel 23,600 ft. Work commenced May 17, 1904 and completed May 17, 1909. Cast iron lining with interior concrete lining. Ext. dia. 23 ft.; int. dia. of concrete lining, 19 ft. Top of tunnel 70 ft. below H. W. and minimum cover 10 ft. Rock, sand, gravel. Average progress in soft ground 7 ft. per day.

Ref. *Trans. Am. Soc. C. E.*, vol. 68.

A-20. Providence. 1904.

Sewer tunnel at Providence, R. I. Length 3,954 ft. Wood lining with brick inside. External diameter about 6 ft. 3 in. Internal diameter 4

ft. Ground dry and wet sand. Progress 9.1 ft. per day. Air pressure 12–14 lb. per square inch. Cost $34.68 per linear foot.

Ref. *Eng. Record,* July 16, 1904.

A-21. Steinway. 1905–1907.

(Also called Belmont tunnels.) Two single track railroad tunnels from Fourth Avenue under 42nd Street and East River to Long Island City, New York. Total length of line about 8,600 ft., of which the greater part is in rock. The shield driven portion aggregates about 5,000 ft. of single track tunnel. Cast iron lining, external diameter 16 ft. 10 in., internal diameter 15 ft. 6 in. Top of tunnel 88 ft. below H. W. and 25 ft. below river bed. Ground, rock, sand and clay. Air pressure 40 lb. per square inch.

Ref. *Eng. Record,* March 3, 1906; June 8, 1907.

A-22. Gowanus. 1907–1908.

Flushing tunnel for Gowanus Canal, Brooklyn, N. Y. Length 6,270 ft. Brick lining. External diameter 14 ft. 8 in. Internal diameter 12 ft. Air pressure 7 lb. per square inch. Cost $100.00 per linear foot.

A-23. Lawrence Avenue Sewer, Chicago. 1907.

(*a*) Intercepting sewer. Length 8,220 ft. Wood lining with interior brick lining. External diameter 20 ft. Internal diameter 16 ft. Ground, clay. Cost $79.75 per linear foot.

(*b*) Intake tunnel for flushing water under Lake Michigan. Length 1,446 ft. Roof shield. Internal dimensions: span 20 ft. 6 in.; height 14 ft. Ground, clay. Air pressure 8 lb. per square inch. Wood lining with interior brick lining in arch and concrete in invert.

Ref. (*a*) *Engineering-Contracting,* Feb. 6, 1907.
(*b*) *Eng. Record,* Dec. 19, 1908.

A-24. Detroit River. 1906–1910.

Two single track railroad tunnels across the Detroit River between Detroit, Mich. and Windsor, Ont. carrying the Michigan Central Railway. Portion under river built by trench method. Shore portion by two "side shields." Overall height of shields 27 ft. 11½ in., overall width 19 ft. 10½ in. Wood lining. Average progress 9 ft. per day. Total length driven by shields 8,876 ft. Air pressure from 7 to 24 lb. per square inch. Cost from $228 to $257 per linear foot of single tunnel.

Ref. *Proc. Inst. C. E.,* vol. 185, pp. 2–91. *Engineering-Contracting,* Sept. 27, 1911. *Eng. Record,* Sept. 19, 1908; Jan. 30, 1909; Dec. 18, Dec. 25, 1909; March 5, 1910. *Trans. Am. Soc. C. E.,* vol. 74. p. 288.

A-25. Beacon Hill. 1909–1911.

Double track railroad tunnel in Boston, Mass. Length driven by roof shield 1,570 ft. Overall width 48.8 ft. No air pressure. Hard sandy clay.

Ref. Boston Transit Commission Annual Report, 1912. *Eng. Record,* July 13, 1912.

A-26. Cleveland New West Side Intake. 1914–1917.

Water intake tunnel under Lake Erie at Cleveland, O. Length 16,088 ft. Concrete block lining. External diameter 11 ft. 11 in. Internal diameter 10 ft.

Ref. *Eng. News,* Jan. 18, 1917.

A-27. Old Slip. 1914–1919.

Two single track railroad tunnels under the East River, New York, from Old Slip, Manhattan, to Clark Street, Brooklyn. Total length 11,700 ft. of single track tunnel. Cast iron lining, two types. (*a*) External diameter 17 ft. 2 in., internal diameter 16 ft.; skin thickness 1 in.; weight 4,070 lb. per linear foot. (*b*) External diameter 17 ft. 6 in., internal diameter 16 ft.; skin thickness 1⅜ in.; weight 6,220 lb. per linear foot. Top of tunnel 71.50 ft. below H. W. Minimum cover *nil.* Average air pressure 30 lb. per square inch; maximum, 37½ lb. Ground, rock, sand. Average progress under river in soft ground 163 ft. per month, in rock 92 ft. per month. Total cost of contract $6,257,392. Cost per linear foot of single tunnel (excluding stations) $450.

A-28. Whitehall. 1914–1920.

Two single track railroad tunnels under the East River, New York, from Whitehall Street, Manhattan, to Montague Street, Brooklyn. Total length 12,814 ft. of single track tunnel. Cast iron lining, two types for shield driven tunnels. External diameter 18 ft., internal diameter 16 ft. 6 in. Type (*a*) skin thickness 1 in.; weight 4,175 lb. per linear foot. Type (*b*) skin thickness 1⅜ in.; weight 6,220 lb. per linear foot. Top of tunnel 70 ft. below H. W. Minimum cover 8 ft. Average air pressure 30 lb. per square inch. Maximum 34½ lb. Ground, rock, sand, clay. Average progress under river in soft ground 198 ft. per month; in rock 94 ft. per month. Total cost of contract $5,712,350. Cost per linear foot of single tunnel (excluding stations) $423.

A-29. Willoughby-Montague Street, Brooklyn. 1915–1916.

Two single track railroad tunnels under Montague and Willoughby Streets, Brooklyn. Total length 6,284 ft. of single tunnel. Cast iron lining. Top of tunnel 55 ft. below surface of street. Normal air pressure. Average progress 180 ft. per month.

A-30. 14th Street, New York. 1916–1919.

Two single track railroad tunnels under the East River, New York, from 14th Street, Manhattan, to North 7th Street, Brooklyn. Total length 14,178 ft. of single track tunnel. Cast iron lining. Shield driven tunnels, external diameter 18 ft., internal diameter 16 ft. 6 in. Top of tunnel 80 ft. below H. W. Minimum cover *nil.* Average air pressure 33 lb. per square inch, maximum 39½ lb. Ground, rock, sand, clay. Average progress under river in soft ground 122 ft. per month, in rock and soft ground 44 ft. per month. Total cost of contract $6,002,800. Cost per linear foot of single tunnel $425 (excluding stations).

A-31. Point Defiance. 1915.

Two track railroad tunnel for Northern Pacific Railway near Tacoma, Wash. Roof shield. Overall width 34 ft. 8¾ in. Wood lining. Heavy ground. Progress 12–16 ft. per day.

Ref. *Eng. Record*, Feb. 27, 1915.

A-32. Hulig Avenue, Memphis. 1915.

Sewer tunnel under Hulig Avenue, Memphis, Tenn. After 560 ft. were driven by shield, the shield distorted and method abandoned. Wood lining with interior concrete lining. External diameter 21 ft. Internal diameter 16 ft.

Ref. *Eng. News*, May 11, 1916.

A-33. Gayoso Avenue, Memphis. 1915.

Sewer tunnel under Gayoso Avenue, Memphis, Tenn. Length 2,805 ft. Wood lining with interior concrete lining. External diameter 19 ft. 8 in., internal diameter 15 ft. Ground, hard clay, soft clay, waterbearing sand. Progress 10 ft. per day.

Ref. *Eng. News*, May 11, 1916.

A-34. Dorchester. 1915–1917.

Two single track tunnels under Fort Point Channel, Boston Harbor, Boston, Mass., between Dorchester Avenue and Summer Street. Total length 6,120 ft. of single track shield driven tunnel. Wood lining with interior concrete lining; external diameter 24 ft. 2 in.: internal diameter 19 ft. 10 in. Ground, blue clay with sand in places. Air pressure 20–28 lb. per square inch. Average progress 10 ft. per day.

Ref. Boston Transit Commission, *Annual Report*, 1916. *Eng. Record*, Aug. 21, 1915; Jan. 29, 1916.

A-35. 60th Street, New York. 1916–1919.

Two single track railroad tunnels under the East River, New York, from 60th Street, Manhattan, to North Jane Street, Queens. Total length 1,754 ft. of single track tunnel driven by shield. Cast iron lining, external diameter 18 ft. Internal diameter 16 ft. 6 in. Top of tunnel 95 ft. below H. W. In the channel west of Blackwell's Island the depth of water is about 115 ft. and the tunnel is built through a permanent clay blanket previously deposited and protected with rip rap. Ground, rock, sand, gravel and clay blanket. Air pressure up to 48-lb. per square inch. Average progress 5.23 ft. per day. Average monthly progress of shield in rock 81 ft., in mixed face 99 ft., in soft ground 184 ft. Total cost of contrac $4,229,000. Cost per linear foot of single track $289 (out of 7,320 ft. of single track structure only 1,754 ft. were shield driven).

A-36. West Water Street, Milwaukee. 1916.

Sewer tunnel. External diameter 7 ft. Wood and concrete lining. Internal diameter 4 ft. Ground, sandy clay. Depth below street surface 15–25 ft. Normal air pressure. Maximum progress 37 ft. in two ten-hour shifts.

Ref. *Eng. News-Record*, Jan. 4, 1917.

A-37. Milwaukee River Siphon. 1917.

Sewer tunnel under Milwaukee River, between Fowler Street at West Water Street and Detroit Street at Broadway. Total length 1,015 ft. External diameter 13 ft. Wood and concrete lining. Top of tunnel 36 ft. below surface of river. Depth of cover 12 ft. Ground, sand, gravel, marshy clay. Air pressure 14–21 lb. per square inch. Average progress 10 ft. per day.

Ref. *Municipal Engineer*, Dec., 1917.

A-38. Milwaukee Sewer. 1918.

Sewer system of Milwaukee. Length 11,000 ft. External diameter 9 ft. 4 in., internal diameter 6 ft. Wood and concrete lining.

Ref. *Eng. News-Record*, April 4, 1918.

A-39. Flatbush Avenue. 1916–1919.

Two track rapid transit railroad tunnel under Flatbush Avenue, Brooklyn,

New York, from Walbone Street North along the east side of Prospect Park for a distance of 1,848 ft. Roof shield. Overall width of shield 36 ft. 6 in. Concrete lining laid wet. Ground, glacial deposit, sand, clay, hard-pan, boulders. Normal air pressure. Progress 155 ft. per month (maximum).

Ref. *Eng. News-Record*, Oct. 27, 1921, pp. 676–681.

A-40. Hudson River Vehicular Tunnel. 1922.

Two tunnels for highway traffic. Each tunnel has a 20 ft. roadway for two lines of vehicles and a footwalk. Across the Hudson River from Canal Street at Washington Street, New York City to 12th Street, Jersey City about 400 ft. east of Provost Street. Length of line 6,870 ft., or 13,740 ft. of tunnel. Cast iron lining with interior concrete lining. External diameter 29 ft. 6 in. except for a length of 777 ft. of the north tunnel at the New Jersey end which is 30 ft. 4 in. external diameter. Overall depth of flange of cast iron lining 14 in. Shield driven. Ground, sand, gravel, rock, clay and silt. Contract price for complete work, including concrete lining and shafts and all interior finish except roadway pavement, $19,333,000.00 or about $1,400.00 per linear foot of tunnel.

England

E-1. Thames Tunnel. 1825–1842.

Under the Thames River between Wapping and Rotherhithe, London, one mile below Tower Bridge. Length 1,506 ft. between shafts. External cross-section rectangular, 37 ft. 6 in. wide and 23 ft. 3 in. high. Brick lining. Internal cross-section, two horseshoe shaped tunnels, 13 ft. 9 in. wide and 15 ft. 9 in. high. Top of structure 43 ft. below H. W. and 13 ft. below river bed. Ground, mud, clay, limestone and sand. First shield driven tunnel. Shield invented and work directed by Marc Isambard Brunel. Compressed air not used. Average progress 6 in. per working day. Built for highway traffic, used as part of the East London Railway system. Cost $2,900,000.00.

Ref. *Weale's Quarterly of Engineering*, vol. 5, 1846. Legouez, 1897, pp. 1–44.

E-2. Tower Subway. 1869.

Under the Thames River between London Bridge and Tower Bridge London. Length 1,320 ft. Circular cast iron lining, external diameter, 7 ft. 1¾ in.; internal diameter 6 ft. 7¾ in. Top of tunnel 63 ft. below H. W. and minimum cover 22 ft. London clay throughout; no compressed air needed or used. Promoted by Peter Barlow and constructed by James Henry Greathead, who designed the shield, the first Greathead shield. Average progress 8 ft. 6 in. per day. Cost of shaft and tunnel, $48,000.00.

Ref. Copperthwaite, 1906, pp. 11–14. Legouez, 1897, pp. 50–54. *Proc. Inst. C. E.*, vol. 123, p. 46.

E-3. London & Southwark Subway. 1886–1890.

Later called *the City & South London Railway*. From the Monument, City of London, under the Thames just above London Bridge, to Clapham Road at Stockwell Road. Two single track tunnels, each 16,640 ft. long or a total length of 33,280 ft. Cast iron lining. For a length of 13,200 ft. the external diameter was 10 ft. 10¾ in. and the internal diameter 10 ft.

2 in. For the remaining 20,080 ft. the external diameter was 11 ft. 3 in. and the internal diameter 10 ft. 6 in. Depth 30–70 ft. below surface. London clay throughout except for a length of 150 ft. at Swan Lane and 600 ft. near Stockwell where waterbearing gravel was met. Compressed air used at these places for the first time in conjunction with shield. Average progress 80 ft. per week. Average cost $72.00 per linear foot.

Ref. *Proc. Inst. C. E.*, vol. 123, Greathead on the City and South London Railway. Legouez, 1897, pp. 62–88.

E-4. Mersey. 1888–1892.

Tunnel for the Vyrnwy Aqueduct under the River Mersey at Fidler's Ferry near Liverpool. Commenced without shield. After 18 months work the contractors abandoned the work with only 60 ft. of tunnel completed. Tunnel relocated and commenced with shield and air pressure. After 180 ft. were driven the second contractor abandoned the work. The shield was then reconstructed and the work proceeded under the directions of the engineer, who completed the work between November, 1891 and March, 1892. Length 800 ft. Cast iron lining, external diameter 10 ft., internal diameter 9 ft. Ground clay, coarse gravel, sand. Top of tunnel 35 ft. below H. W. Average progress 34 ft. per week, maximum 57 ft. Air pressure average 17 lb. per square inch.

Ref. Simms "Practical Tunneling," pp. 449–465. *Proc. Inst. C. E.*, vol. 123, pp. 100–105. Legouez, 1897, pp. 62–88. Copperthwaite, 1906, pp. 223–230. Deacon "Tunneling in Loose Ground," *British Assoc. Adv. Sci. Edinb.* 1892. p. 532 *Eng. Record*, July 16, July 23, July 30, Sept. 17. 1892.

E-5. Blackton. 1889.

Middlesbrough Water Works. Length 426 ft., cast iron lining, internal diameter 13 ft. 6 in. Ground Schist. No air pressure.

E-6. Kingston. 1891.

Tunnel for water pipes, Southwark and Vauxhall Water Works, under the River Thames at Kingston, London. Length 540 ft. Cast iron lining, external diameter 9 ft., internal diameter 8 ft. 4 in. No air pressure, London clay throughout. Cost $40.00 per linear foot.

E-7. Blackwall. 1892–1897.

Highway tunnel under the Thames from Poplar to East Greenwich, London. Length 3,116 ft. of shield driven tunnel. Cast iron lining with interior concrete lining. External diameter 27 ft., internal diameter of concrete 24 ft. 3 in. Top of tunnel 53 ft. below H. W. Minimum cover 5 ft. 6 in. Ground clay, gravel, sand. Average progress under the river (1,200 ft.) 23 ft. per week. Maximum air pressure 37 lb. per square inch. Cost with heavy cast iron lining $605.00; with light lining $503.00 per linear foot.

Ref. *Proc. Inst. C. E.*, vol. 130. Copperthwaite, 1906, pp. 180–215. Legouez, 1897, pp. 227–252.

E-8. Waterloo & City. 1894–1898.

London Tube Railway. Two single track tunnels from Mansion House, City of London, crossing under the Thames to Waterloo Station. Begun 1894, completed 1898. Total length of single track tunnel 16,740 ft. Cast iron lining. External diameter from Mansion House to South bank of River Thames, 13 ft. Internal diameter 12 ft. 1¼ in. From the Thames

to Waterloo, external diameter 13 ft. 7¼ in., internal diameter 12 ft. 9 in. Ground, London clay, except near Waterloo Station where waterbearing ground was met. Air pressure, 7 to 8 lb. per square inch. The station at Mansion House 330 ft. long, cast iron lined and shield driven. External diameter 24 ft. 6 in. Internal diameter 23 ft.

Ref. *Proc. Inst. C. E.* vol. 189.

E-9. Central London Railway. 1896.

London Tube Railway. Two single track tunnels from Bank, City of London to Shepherds Bush. Length of line 5.9 miles, opened for traffic July, 1900. Extension from Shepherds Bush to Wood Lane, 0.6 mile long, opened for traffic, May, 1908. Extension from Bank to Liverpool Street opened, July, 1912. Length 0.5 mile. Total length of single track tunnel 14 miles. Cast iron lining. External diameter, 12 ft. 6 in. Internal diameter, 11 ft. 8¼ in. Station tunnels cast iron lined and shield driven. External diameter 22 ft. 6 in., internal diameter 21 ft. 2½ in.

Ref. *Engineering*, Feb. 18 and March 18, 1898. *Engineer*, Nov. 4, 11 and 18, 1898. Copperthwaite, 1906, pp. 104–113.

E-10. City & South London Railway.

London Tube Railway. The portion of the original line (E-3) between Monument and the south side of the Thames was reconstructed in 1900 (0.5 mile of railroad). Extension from Stockwell Road to Clapham Common in 1900. Length one mile. Extension from Monument to Moorgate Street, 1900, length 0.5 mile. Extension to Angel, Islington, 1901, 1.5 mile route length. Extension to Euston Station, 1.3 mile, 1907. Total length of single track tunnels, 9.6 miles. Cast iron lining. External diameter 11 ft. 3 in. Internal diameter 10 ft. 6 in. Station tunnels lined with cast iron and shield driven. External diameter 22 ft. 6 in., and 34 ft. 6 in.

E-11. Greenwich. 1899–1901.

Footway tunnel under the Thames between the southerly point of Isle of Dogs, Poplar and Greenwich, London. Length 1,183 ft. Cast iron lining, external diameter 12 ft. 9 in., internal diameter 11 ft. 9 in. Top of tunnel 54 ft. below H. W. and 10 ft. below river bed. Ground, clay, sand and gravel. Average progress 32 ft. per week. For a period of 3 months the average progress was 10 ft. per working day. Cost of tunnel, $173.00 per linear foot. Average air pressure 22 lb.; maximum 28 lb. per square inch.

Ref. *Proc. Inst. C. E.*, vol. 150, pp. 230–258. Copperthwaite, 1906, pp. 230–258.

E-12. Great Northern & City Railway.

London Tube Railway. From Moorgate Street, City of London to Seven Sisters Road, Finsbury. Length of line, 3.5 miles or 7 miles of single track tunnel. Open for traffic February, 1904. Upper half of tunnel lined with cast iron. External diameter, 17 ft. Lower half lined with brick.

Ref. Copperthwaite (1906) pp. 66–69.

E-13. Lea. 1900–1901.

Sewer Tunnel under River Lea, West Ham, London. Length 1,100 ft. Cast iron lining with inner masonry lining. External diameter 12 ft. 3¾ in. Internal diameter of masonry lining 10 ft. 6 in. Ground, sand, peat. Compressed air used.

Ref. Copperthwaite (1906) pp. 258–264.

E-14. Chelsea. 1901.

Water tunnel under the Thames between Chelsea and Wandsworth.

E-15. Bakerloo.

London Tube Railway. From Baker Street crossing the Thames to Elephant and Castle, South London. Length of line 3.8 miles opened in 1906. Extension from Baker Street to Edgware Road (0.6 mile) open in 1907. To Paddington Station (0.4 mile) open in 1913. To Queens Park (2.0 miles). Total length 13.6 miles of single track tunnel. External diameter 12 ft. 9¾ in. Internal diameter, 12 ft. Cast iron lining.

Ref. *Proc. Inst. C. E.*, vol. 150, pp. 25–84.

E-16. Hilsea Creek. 1903.

Water tunnel under Hilsea Creek near Cosham, Hampshire. Length 579 ft., cast iron lining; external diameter 12 ft. 6 in., internal diameter 11 ft. 10 in. Top of tunnel 44 ft. below H. W. and 32 ft. below river bed. Ground, loose waterbearing chalk. No air pressure. Average progress 30 ft. per week.

Ref. Copperthwaite (1906) pp. 363–365.

E-17. Rotherhithe. 1904–1908.

Highway tunnel under the Thames between Stepney and Rotherhithe, about one-quarter mile below the first Thames tunnel (E-1). Length of shield driven tunnel 3,688 ft. 6 in. Cast iron lining with interior concrete lining. External diameter 30 ft. Internal diameter of concrete lining 27 ft. Top of tunnel 45 ft. below H. W.; minimum cover 8 ft. Ground clay, sand, sandy clay, gravel, rock. Average progress 38 ft. per week. Air pressure 21 lb. per square inch. Cost $667.00 per linear foot.

Ref. *Proc. Inst. C. E.*, vol. 175. *Eng. News*, Dec. 19, 1907, pp. 663–669. *Eng. Rec.*, Sept. 11, 1909, pp. 297–299.

E-18. Kingsway. 1904.

Two single track street railway tunnels under Holborn, London. Length of each 250 ft., or 500 ft. total. Cast iron lining external diameter 15 ft. 10 in., internal diameter 15 ft. London clay. Average progress 5 ft. per day.

Ref. *Proc. Inst. C. E.* vol. 183. p. 21.

E-19. Piccadilly. 1906.

London Tube Railway. From Finsbury Park to Hammersmith. Length of line, 9 miles, opened December, 1906. Extension from Holborn to Strand 0.3 mile opened November, 1907. Total length, 18.6 miles of single track tunnel.

E-20. Charing Cross Euston & Hampstead Ry. 1907.

London Tube Railway. From Charing Cross to Golders Green with branch from High Street, Camden, to Holloway Road at Highgate. Length of line 8 miles, opened June, 1907. Extension to Thames Embankment, length 0.3 miles, opened April, 1914. Total length, 16.6 miles of single track tunnel. External diameter, 12 ft. 6 in. Internal diameter 11 ft. 8 in.

Ref. Copperthwaite, 1906, pp 113–116.

E-21. Woolwich. 1910–1912.

Footway tunnel under the Thames between North Woolwich and South

Woolwich, London. Length 1,630 ft. Cast iron lining, external diameter 12 ft. 8 in., diameter of interior concrete 11 ft. 2 in. Top of tunnel 61 ft. below H. W. Minimum cover 12 ft. Ground fissured chalk. Air pressure 18–28 lb. per square inch. Average progress 8 ft. 6 in. per day. Cost complete $410,000.00.

Ref. *The Surveyor and Municipal and County Engineer*, Nov. 1, 1912.

E-22. Twickenham. 1914.

Water tunnel under the Thames between Twickenham and Richmond. Length 618 ft. Cast iron lining, external diameter 16 ft.

Scotland

S-1. Glasgow Harbor. 1890–1893.

Three parallel tunnels under the River Clyde between Ferry Road and Finnieston Quay. The two outer tunnels carry vehicular traffic and the middle tunnel foot passengers. Distance between shafts 705 ft. Total length of shield driven tunnel 1,905 ft. Cast iron lining. External diameter 17 ft., internal diameter 16 ft. Top of tunnels 46 ft. below H. W. and 15 ft. below river bed. Ground, boulder clay, sand, gravel. Maximum air pressure 18 lb. per square inch. Progress 60–90 ft. per month.

Ref. *Engineering*, May 10, May 31, June 14, June 28, 1895. Copperthwaite, 1906, pp. 152–156. Legouez, 1897, pp. 176–189.

S-2. Glasgow District. 1892–1896.

Two single track railroad tunnels for the Glasgow District Subway. Greater part constructed without shield, but approximately 2 miles were constructed with shield and lined with cast iron. External diameter 12 ft., internal diameter 11 ft.

Ref. *Proc. Inst. of Engineers and Shipbuilders in Scotland*, Jan. 28, 1896. Copperthwaite, 1906, pp. 139–143. Legouez, 1897, pp. 190–199.

S-3. Mound of Edinburgh. 1893–1894.

Two tunnels for single line vehicular traffic under a hill. Each tunnel is 750 ft. long. External diameter 17 ft. 6 in., internal diameter 16 ft. 4 in. Dry ground. An air pressure of 15 lb. per square inch used to support the ground. Cast iron lining.

Ref. Copperthwaite (1906) p. 156. Legouez, 1897 p. 357.

S-4. Dee Sewer. 1904–1909.

Sewer tunnel under the River Dee, Aberdeen. Length 331 ft. Cast iron lining, external diameter 8 ft. 6 in; internal diameter 7 ft. 8 in. Top of tunnel 41 ft. below H. W. and 20 ft. below river bed. Air pressure 17 lb. per square inch. Progress 110 ft. per month.

Ref. *Eng. Record*, Dec. 4, 1909.

S-5. Dee Aqueduct. 1919–1920.

Aqueduct tunnel under the River Dee at Aberdeen. Length 759 ft. Cast iron lining, internal diameter 8 ft. Ground, fine waterbearing sand. Progress 152 ft. per month.

Ref. *Engineering and Contracting*, 1921, p. 299.

Ireland

I-1. Brackenagh. 1903.

Water supply tunnel for Belfast through a hill. Greater part built

without shield, but a length of 660 ft. through waterbearing sand was constructed with shield. External diameter 6 ft. Internal diameter 5 ft. 4 in. Maximum depth below surface 95 ft.

Ref. Copperthwaite (1906) pp. 362–363.

France

E-1. Siphon de Clichy. 1892–1894.

Sewer tunnel across the River Seine, Paris. Length 1,522 ft. Cast iron lining; external diameter 8 ft. 2½ in.; internal diameter 7 ft. 6½ in. Top of tunnel 51 ft. below water level and 40 ft. below river bed. Ground, fissured marl and linestone, sand. Air pressure 40 lb. per square inch. Progress 6½–10 ft. per day.

Ref. Legouez, 1897, pp. 253–267. Copperthwaite (1906) pp. 157–158.

F-2. Siphon de la Concorde. 1895–1896.

Sewer tunnel across the River Seine, Paris. Length 780 ft. Cast iron lining; external diameter 6 ft. 6½ in., internal diameter 5 ft. 10¾ in. Top of tunnel 35 ft. below water level and 16 ft. below river bed. Ground, clay, sand. Progress 7–10 ft. per day.

Ref. Legouez, 1897, pp. 267–280.

E-3. Collecteur de Clichy, Extra Muros. 1895–1897.

Sewer tunnel under Boulevard National, Paris. Length 5,750 ft. Oval cross-section. Vertical external diameter 19 ft. 4 in., horizontal external diameter 23 ft. 7½ in. Roof shield. Brick lining. Top of tunnel from 2 to 12 ft. below street level. Loose sandy ground. Average progress about 15 ft. per day.

Ref. Legouez, 1897, pp. 305–326. Copperthwaite (1906) pp. 277 to 283.

F-4. Collecteur de Clichy, Intras Muros. 1896–1897.

Sewer tunnel under Avenue Clichy and Rue Clichy, Paris. Length 8,450 ft. Same cross-section as (F-3). Complete shield. Concrete block lining. Top of tunnel 12–108 ft. below street level. Progress 10 ft. per day.

Ref. Legouez, 1897, pp. 327–348. Copperthwaite (1906) pp. 284–290.

F-5. Siphon de l'Oise. 1897–1898.

Sewer tunnel under the River Oise near Paris. Length 919 ft. Concrete lining. External diameter 8 ft. 3 in., internal diameter 6 ft. 7 in. Ground, sand. Depth below water level 43 ft. Maximum air pressure 24 lb. per square inch. Average progress 2½ ft. per day.

Ref. Copperthwaite (1906) pp. 290–294.

F-6. Collecteur de Bievre.

Sewer tunnel Paris along bank of R. Seine. Part of sewer built by roof shield. Elliptical cross section. Internal dimensions 16 ft. 2 in. horizontal, 10 ft. 10 in. vertical. Part circular cross section constructed with roof shields, internal diameter 13 ft. 2 in. Masonry lining. Total length 8,025 ft.

Ref. Copperthwaite, 1906. p. 379.

F-7. Loing and Lumain Aqueduct. 1898.

Concrete lining. Internal diameter 8 ft. 2½ in. Method abandoned.

Ref. Copperthwaite (1906) p. 379.

F-8. Meudon. 1898.

Two track railroad tunnel between Issy and Viroflay. Roof shield. Method abandoned. Concrete block lining. Width of tunnel 29 ft. 6 in., height, 24 ft.

Ref. Copperthwaite (1906) p. 379.

F-9. Orleans Railway. 1898.

Two track railroad on the south side of the River Seine between Pont d'Austerlitz and Pont de Solferino, Paris. Roof shield. Length constructed by roof shield about 4,000 ft. Overall width of shield 32 ft. Minimum depth from top of shield to street level 1 ft. 3 in. Masonry lining. Normal air pressure.

Ref. Copperthwaite (1906) pp. 294–302.

F-10. Metropolitain Railway, Paris. 1898–1903.

Two track railroad tunnel. Total length of line 45,780 ft., of which 8,352 ft. were built by means of roof shields, of which 11 were used. Several of these were abandoned after being used short distances.

Ref. Copperthwaite, 1906, pp. 324–338.

F-11. Metropolitain Railway, Paris. 1905.

Two track railway tunnel from Vincennes to Porte Maillot, Paris. Roof shield used successfully for a distance of about 2,000 ft. in sandy ground but abandoned after entering faulty rock.

Ref. Copperthwaite, 1906, pp. 357–362.

F-12. Concorde Metropolitain, Paris. 1908–1911.

Two track railroad tunnel under the River Seine. Length 2,030 ft. Cast iron lining, external diameter 25.51 ft., internal diameter 23.94 ft. Top of tunnel 40 ft. below water level. Ground, sand, marl, gravel, limestone. Average progress 3 ft. per day.

Ref. *Proc. Inst. C. E.*, vol. 188, pp. 380–408.

Germany

G-1. Spree. 1896–1899.

Street railway tunnel under the River Spree between Stralau and Trepow, Berlin. Length of shield driven portion 1,225 ft. Rolled steel lining with interior concrete lining. External diameter 13.1 ft.; internal diameter 12.3 ft. Ground, waterbearing sand. Top of tunnel 26 ft. below water level. River 10 ft. deep. Average progress 4.6 ft. per day. Air pressure used.

Ref. *Handbuch der Ingenieur Wissenschaften.* I. 1920, pp. 431–434.

G-2. Isebech-Millernthor Sewer, Hamburg. 1899–1904.

Brick lined sewer tunnel in Hamburg. Length 7,050 ft. External diameter 10 ft.; internal diameter 7 ft. 10½ in. Depth below street surface 20–60 ft. Average progress 4 ft. 3 in. per day. Air pressure 9–21 lb. per square inch.

Ref. *Deutche Bauz.* 1907, p. 254, 263, 270, 278, 286, 295, 309.

G-3. Hafenstrasse-Kuhmuhle Sewer, Hamburg. 1899–1904.

Brick lined sewer tunnel in Hamburg. Length 3,470 ft., driven in normal air. External diameter 12 ft.; internal diameter 9 ft. 10½ in. Depth below street surface 20 ft. Progress 5 ft. 9 in. per day.

Ref. see G-2.

G-4. Elbe. 1909–1910.

Two single line traffic roadway tunnels under the River Elbe, Hamburg, between St. Pauli and Steinwarder. Length of each tunnel 1,500 ft., or a total length of 3,000 ft. of tunnel. Rolled steel lining, with interior concrete lining. External diameter 19 ft. 5 in.; internal diameter 17 ft. 8½ in. Top of tunnel 52 ft. below H. W. and 19 ft. below river bed. Ground, sand, clay. Air pressure 29–38 lb. per square inch. Average progress 5½ ft. per day.

Ref. *Handbuch der Ingenieur Wissenschaften*, I. 1920, pp. 437–441.

G-5. Wanne. 1911.

Canal tunnel under the railroad station at Wanne; Essen-Ruhr. Brick lining. External diameter 9 ft. 3 in.; internal diameter 6 ft. 7 in. Water-bearing sand and marl. Top of tunnel 25 ft. below surface.

Ref. *Der Eisenbahntunnel*, by Dolezalek, 1919, pp. 169–170.

G-6. Hörde. 1911.

Canal tunnel, length 4,000 ft.

G-7. Gelchenkirchen. 1911.

Canal tunnel under streets at Gelchenkirchen. Length 2,200 ft. Concrete lining. External diameter 12 ft. 9 in.; internal diameter 10 ft. 3 in. Top of tunnel 40 ft. below surface of ground. Air pressure used. Average progress 17 ft. per day.

Ref. *Zentralblatt der Bauverwaltung*, Nov. 25, 1911, pp. 597–600.

G-8. Kiel Canal. 1912–1913.

Canal tunnel under the Kiel Canal at Kiel. Length 2,540 ft. Rolled steel lining with interior concrete lining. External diameter 11 ft.; internal diameter 9 ft. 10 in. Top of tunnel 50 ft. below water level and 13 ft. below canal bed. Compressed air used. Ground, sandy clay. Average progress 5½ ft. per day.

Ref. *Zeitschrift des Vereines deutcher Ingenieure.* March 13, 1915, pp. 215–221; April 10, 1915, pp. 295–300.

G-9. Bochum. 1913.

Canal tunnel at Bochum. Length 1,550 ft., external diameter 12 ft. 9 in.; internal diameter 10 ft. 3 in. Air pressure 8 lb. per square inch. Concrete lining. Progress 20 ft. per day.

Ref. *Handbuch der Ingenieur Wissenchaften*, I. 1920, pp. 446–447.

G-10. Elm. 1913.

Two track railroad tunnel at Elm on the Prussian Railroad. Greater part of the tunnel, which has a total length of 11,700 ft., done without shield, but short portions in bad ground were shield driven. Cross-section horseshoe shaped, height of shield 36 ft., width, 37 ft. 9 in. Progress 2½ ft. per day. Lining, concrete with steel girders, spaced 3 ft. 3 in. apart.

Ref. *Der Eisenbahntunnel*, by Dolezalek, 1919, p. 95 and p. 165.

G-11. Essen.

Small canal tunnel with brick lining. Length 590 ft.

G-12. Dorstfeld.

Tunnel under railroad at Dorstfeld. Length 2,630 ft.

G-13. Kiel.

Canal tunnels within the Kiel district. Total length 4,000 ft. Concrete lining, compressed air used.

G-14. Hamburg Sewers.

Sewer tunnels in Hamburg, total length 8,000 ft.

Cuba

C-1. Havana Sewer. 1910.

Sewer tunnel under Havana harbor. Length 1,200 ft. External diameter 10 ft., internal diameter 7 ft. Wood lining with interior concrete lining.

Australia

In connection with the sewer system of Melbourne about 7 miles of tunnel were driven by shield between 1893 and 1898. The tunnels are tabulated below.

Ref. No.	Section	Type of lining	External diameter	Internal diameter	Length	Length under air pressure
M- 1	Hobson Bay, section 1	cast iron	11′ 0″	9′ 0″	900′	500′
M- 2	Hobson Bay, section 1	cast iron	11′ 0″	9′ 0″	633′	
M- 3	Hobson Bay, section 2	concrete	11′ 0″	8′ 6″	1,300′	
M- 4	Hobson Bay, section 2	concrete	11′ 3″	8′ 9″	4,900′	
M- 5	Hobson Bay, section 2	concrete	11′ 6″	9′ 9″	3,000′	
M- 6	Hobson Bay, section 3	concrete	10′ 6″	8′ 0″	960′	700′
M- 7	Hobson Bay, section 4	cast iron	5′ 9″	4′ 3″	2,070′	1,430′
M- 8	Hobson Bay, section 4	bluestone	5′ 10½″	4′ 3″	1,290′	
M- 9	Hobson Bay, section 5	bluestone	5′ 10½″	4′ 3″	1,327′	
M-10	Hobson Bay, section 5	cast iron	5′ 9″	4′ 3″	1,611′	1,486′
M-11	Hobson Bay, section 5	bluestone	5′ 10½″	4′ 3″	1,200′	
M-12	South Yarra section 1	bluestone	9′ 0″	6′ 9″	1,760′	
M-13	Richmond, section 1	cast iron	6′ 0″	4′ 3″	704′	494′
M-14	Melbourne, section 1	cast iron	5′ 9″	3′ 3″	1,440′	450′
M-15	Melbourne, section 1	cast iron	4′ 10½″	3′ 3″	3,440′	
M-16	Melbourne, section 1	concrete	5′ 9″	3′ 3″	860′	
M-17	Melbourne, section 1a	cast iron	5′ 9″	3′ 3½″	247′	247′
M-18	North Yarra, section 1	bluestone	....	11′ 0″	496′	
M-19	North Yarra, section 1	cast iron	9′ 9″	7′ 9″	5,280′	
M-20	North Yarra, section 6a	wood	10′ 6″	7′ 6″	1,270′	
M-21	North Yarra, section 6a	wood	9′ 9″	6′ 9″	1,990′	
M-22	North Yarra, section 4	cast iron	....	....	467′	

The cast iron lined tunnels had an internal lining of concrete. The concrete lined tunnels were built of concrete blocks. The wood lining was made up in segments similar to cast iron lining.

Ref. *Victorian Institute of Engineers*, August 3, 1898. *Eng. News*, Feb. 7, 1901.

CHAPTER V

SIZE AND SHAPE OF TUNNELS

1. Cross-section.—The size of a tunnel is fixed by the internal clearance required for its use and by the design of the lining. Owing to the character of the external pressures a curved cross-section for the lining is usually most economical.

2. Internal Clearance.—The internal clearance should be large enough, not only for the free passage of the traffic for which the tunnel is intended, but also for the facilities needed for maintenance of traffic. For economy of construction the space needed for the facilities should be so arranged within the shape imposed by the curvature of the lining, that no space is wasted.

3. Internal Cross-section of Existing Tunnels.—For guidance in determining the internal cross-section for any given purpose the internal cross-sections of various existing tunnels are shown as follows:

4. Rapid Transit Tunnels.—In addition to the space necessary for the track structure and the car, equipped with signal lamps, contact shoes and other appurtenances, tunnels for rapid transit railroads must have a clearance to allow for deviations of the car due to swaying, broken springs, etc. Outside of the clearance line thus determined there should be room for signals, wires, cables, lights, pipes and other facilities needed for the operation of the railroad. If the windows of the car can be opened, there should be a clear space of about 18 in. between the side of the

car and the side of the tunnel to prevent accident to the passengers, and the appurtenances in the tunnel should be arranged so as to be clear of the space within reach of the windows. If

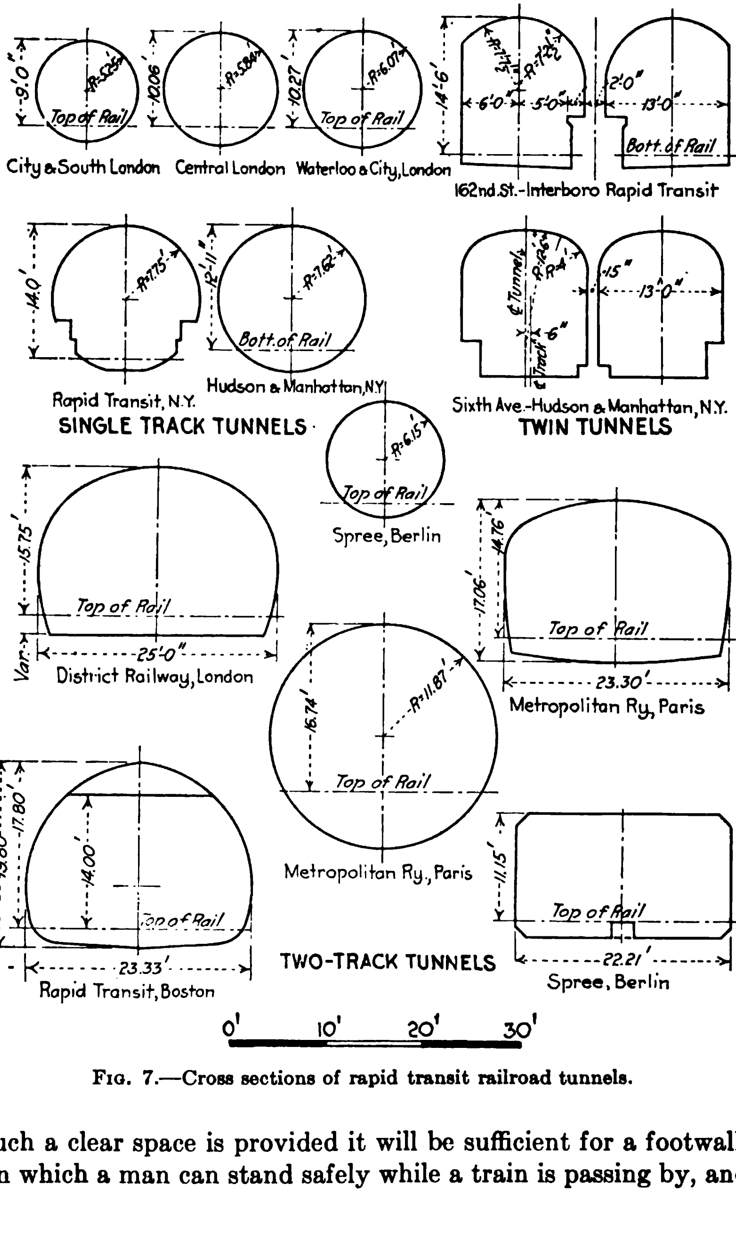


FIG. 7.—Cross sections of rapid transit railroad tunnels.

such a clear space is provided it will be sufficient for a footwalk on which a man can stand safely while a train is passing by, and

which will serve to remove the passengers from a stalled train in an emergency without danger from the contact rail.

5. Station Tunnels.—At stations the tunnels must be widened to make room for the platform. It is absolutely essential for efficient service of the railroad that the platform be wide enough

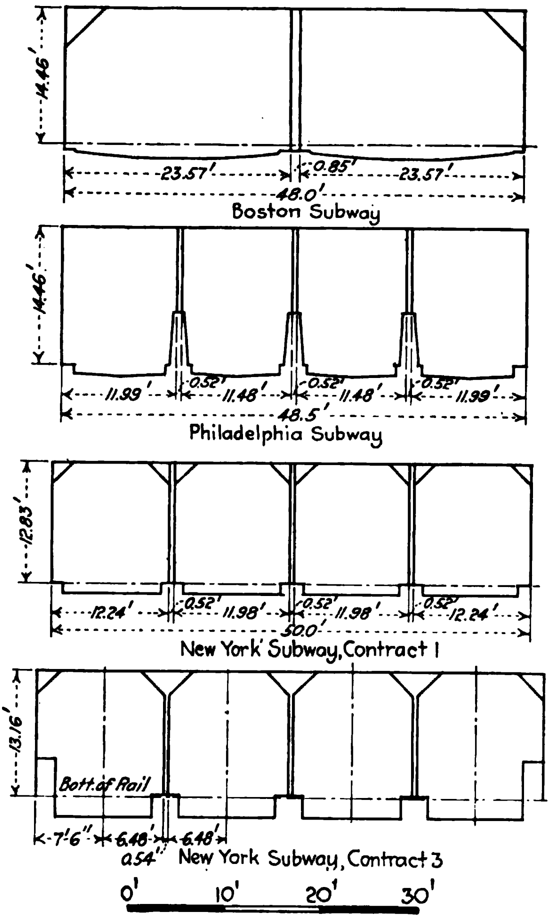


FIG. 8.—Cross sections of rapid transit subway tunnels.

and long enough to handle the traffic that the railroad may carry. Traffic frequently increases rapidly in a short time and it is better at the time of construction to provide sufficient platform space than either to have the efficiency decreased by too little space or to be forced to reconstruct the station under traffic.

6. Railroad Tunnels.—Generally speaking, the same conditions as regard clearances will apply to railroad tunnels as to those for rapid transit lines. Railroad tunnels are usually made wide

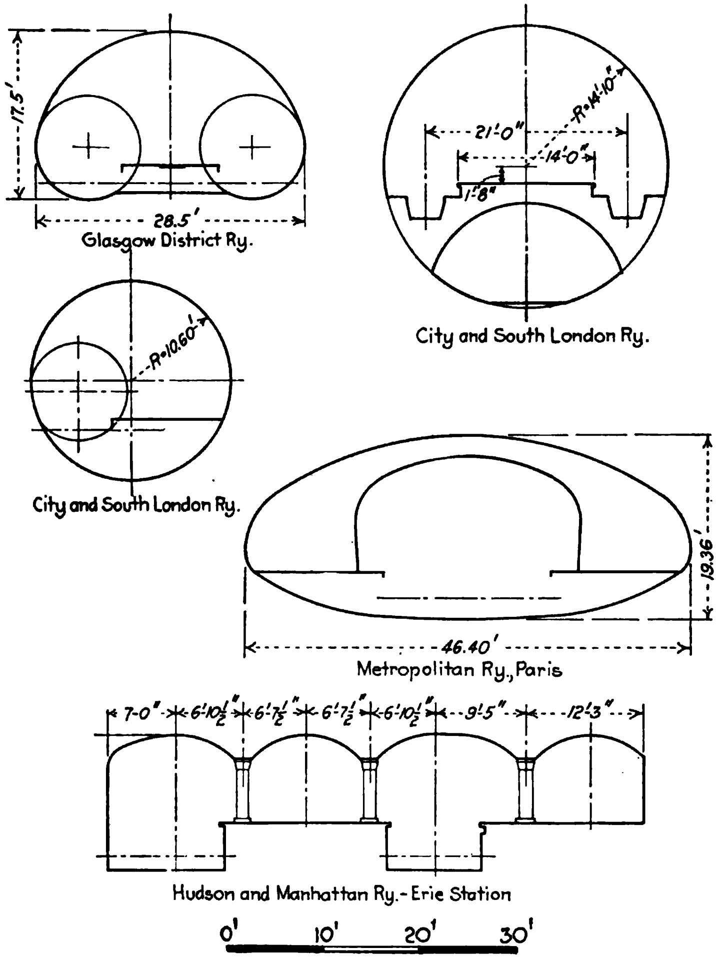


FIG. 9.—Cross sections of rapid transit railroad station tunnels.

enough to provide a walking space between the car and the tunnel wall. Some American railroad tunnels are built of a height sufficient to permit a man to stand upright on a car passing through the tunnel. This does not apply to shield driven tunnels.

7. Highway Tunnels.—In addition to a roadway for vehicular traffic a highway tunnel is usually provided also with one or two sidewalks for pedestrians. In a tunnel where the vehicular traffic is heavy sidewalks should be provided even if the tunnel is not intended for the use of foot passengers. These sidewalks are used by the police patrolling the tunnel and by persons connected with the maintenance of the tunnel or dealing with a broken down car. Such sidewalks may be made high above the roadway so as to afford a better view of the tunnel and the traffic in it.

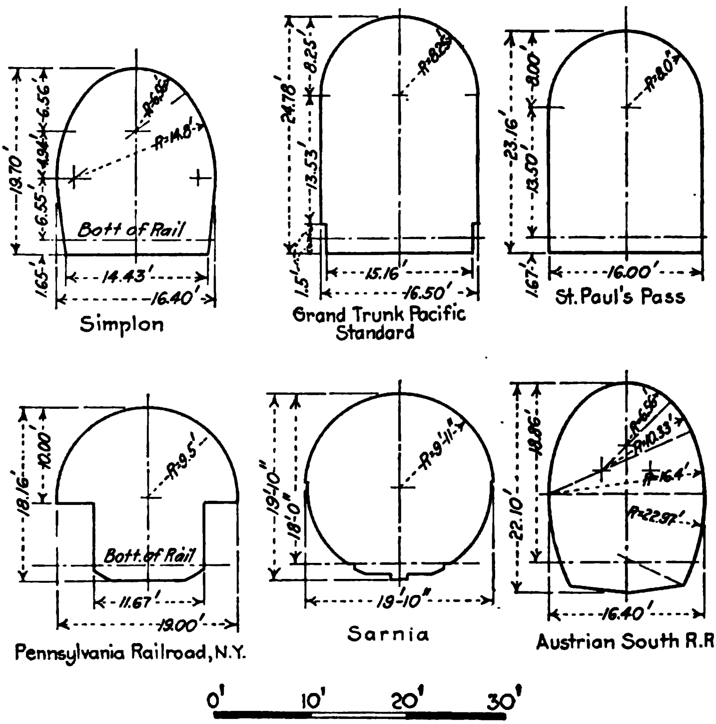


FIG. 10.—Cross sections of railroad tunnels—single track.

8. Width and Height of Highway Tunnels.—The question of the proper width and overhead clearance of a roadway through a tunnel is still uncertain. In connection with the forthcoming construction of the vehicular tunnel under the Hudson River at New York careful studies have been made of this question and it has been concluded that for two lines of traffic moving in the same direction at regulated speed, the proper width is 20

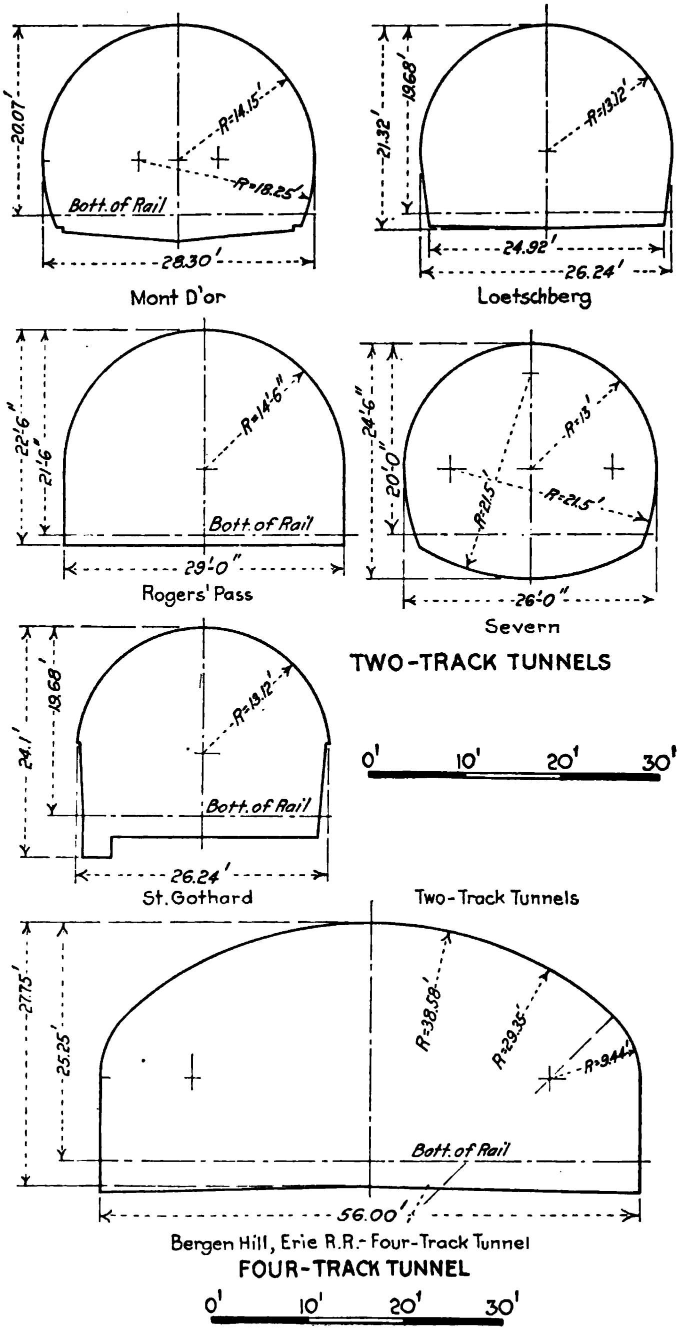


FIG. 11.—Cross sections of railroad tunnels—two- and four-track.

ft. and for three lines of traffic the width should be 28 ft. Further it has been concluded that the overhead clearance should be 13 ft. 6 in. These dimensions, however, are local and depend on

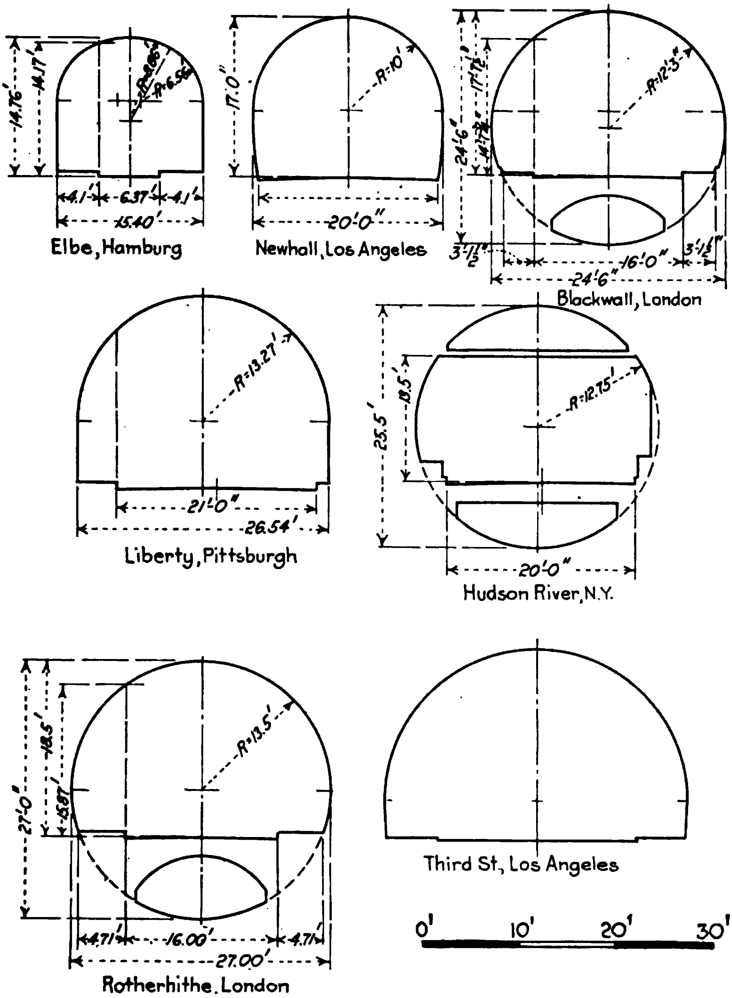


FIG. 12.—Cross sections of highway tunnels—one- and two-way.

usage and regulations. The problem is new, particularly as to the width of the roadway, and only experience will show just what width is required for several lines of fast moving automobiles to pass through a tunnel.

9. Ventilation of Highway Tunnels.—An automobile develops from 0.64 to 2.11 cu. ft. of carbon monoxide gas per minute while running, and dissipates it into the air in the tunnel. These figures are taken from tests made for the Hudson River Vehicular Tunnel and the general result of the tests is that "the exhaust

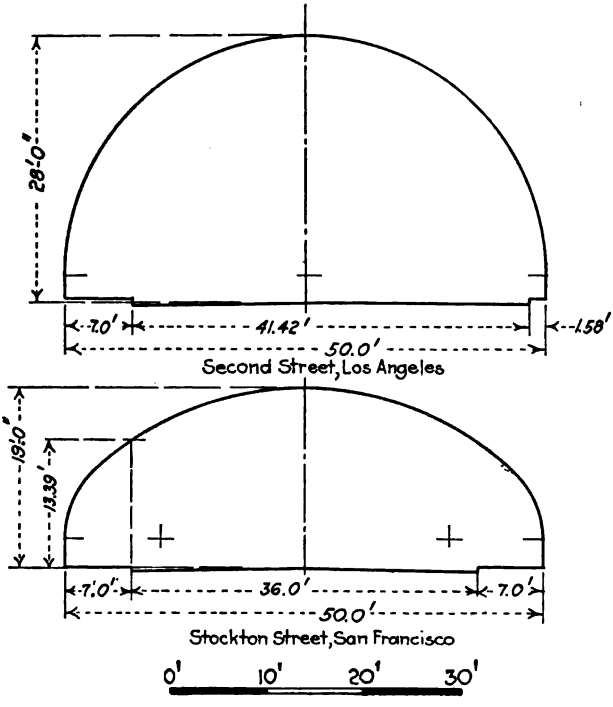


FIG. 13.—Cross sections of highway tunnels—four-way.

gases contained about 6.8 per cent of the carbon monoxide and 8.4 per cent of carbon dioxide, developing only 67 per cent of the heat value of the gasoline." (*Journal Am. Soc. of Heating and Ventilating Engineers*, vol. 27, No. 3, April 1921.) A human being can stand with safety and without discomfort for about one hour an average of 4 parts of carbon monoxide in 10,000 parts of air breathed. Risk of considerable discomfort would begin at from 8 to 9 parts of carbon monoxide in 10,000 parts of air for periods of an hour when at rest and for shorter periods during exertion. Actual danger begins with concentrations not much higher and periods not much longer. It is apparent, therefore, that when the tunnel is long and the traffic dense, artificial ven-

tilation must be provided. Discomfort has been felt in a tunnel about 1,200 ft. long by the passengers riding through it when the traffic has been blocked for a period of about 30 minutes. The volume of fresh air required for ventilation is a question not yet fully answered but one to which much thought is being given. It is to be hoped that some day means will be found whereby automobiles will be able to consume their own poisonous gases.

10. Methods of Ventilation.—When the tunnel is short the ventilation may be carried out by sending a current of air from one end to the other through the tunnel, but when the volume of air necessary for ventilation is large this method becomes imprac-

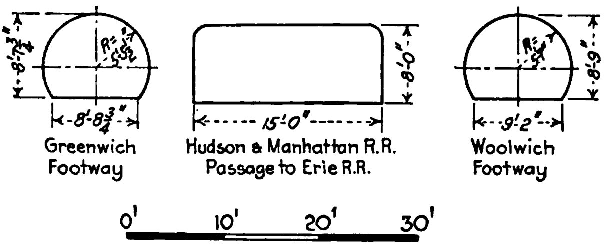


FIG. 14.—Cross sections of footway tunnels.

ticable, because the velocity of the current will be too great for comfortable, or even possible, use of the tunnel and also on account of the danger of spreading a fire in the tunnel. A current of ventilating air through a tunnel should be blown in the same direction as the traffic is moving, because if a car catches fire in the tunnel the cars in front of it can escape while those behind will not be so severely exposed. If the current of air is blown in the opposite direction the cars behind will have no means of escape.

11. Cross-ventilation.—When direct ventilation is not sufficient, fresh and foul air ducts must be placed through the tunnel. The velocity of the air through these ducts may be much higher than that possible through the traffic space and consequently, a larger volume of air may be introduced into the tunnel. The air may be blown across the traffic space from the fresh to the foul air duct and thus relieve the tunnel from through currents. The space occupied by these ducts must be taken into account in determining the cross-section of the tunnel and may add appreciably to the size of the tunnel.

12. Footway Tunnels.—For mental comfort of the passengers a footway tunnel should have a reasonably large height and

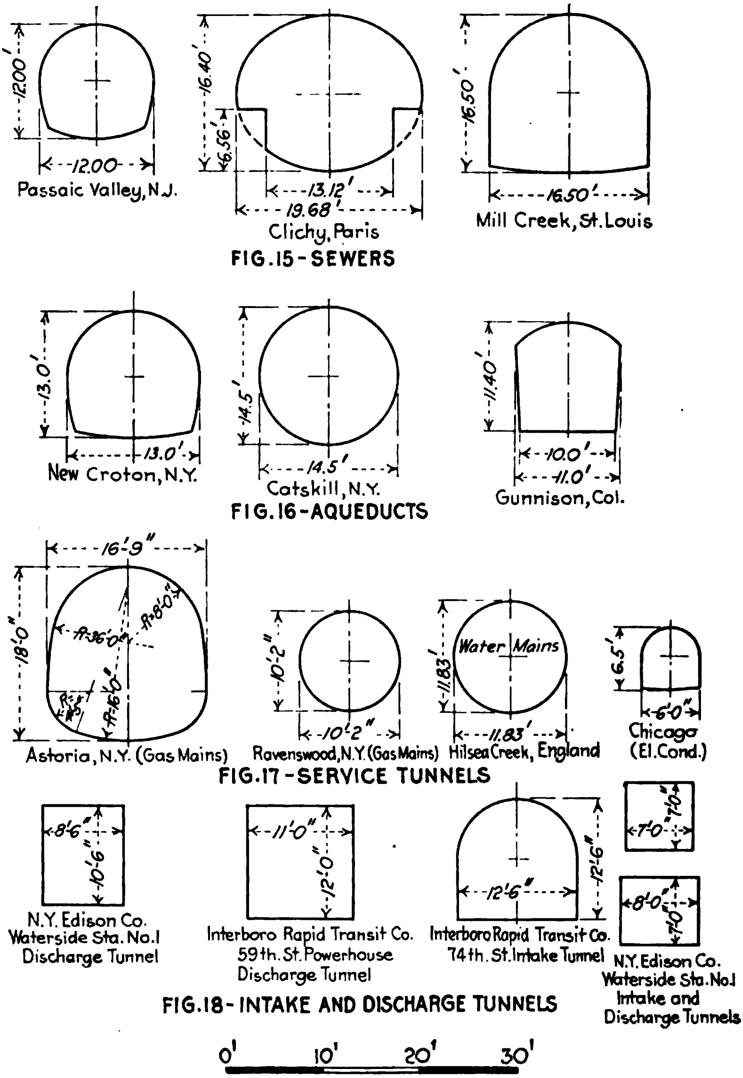


Fig. 15.—Cross sections of sewer tunnels.

Fig. 16.—Cross sections of aqueduct tunnels.

Fig. 17.—Cross sections of service tunnels.

Fig. 18.—Cross sections of water intake and discharge tunnels.

width. The headroom should not be less than 8 ft. and prefer-

ably 9 ft. or more. The width is naturally determined by the volume of the traffic.

13. External Cross-section of Tunnels.—The external cross-section of a tunnel is determined by the internal cross-section, the external pressures, the lining materials and the method of

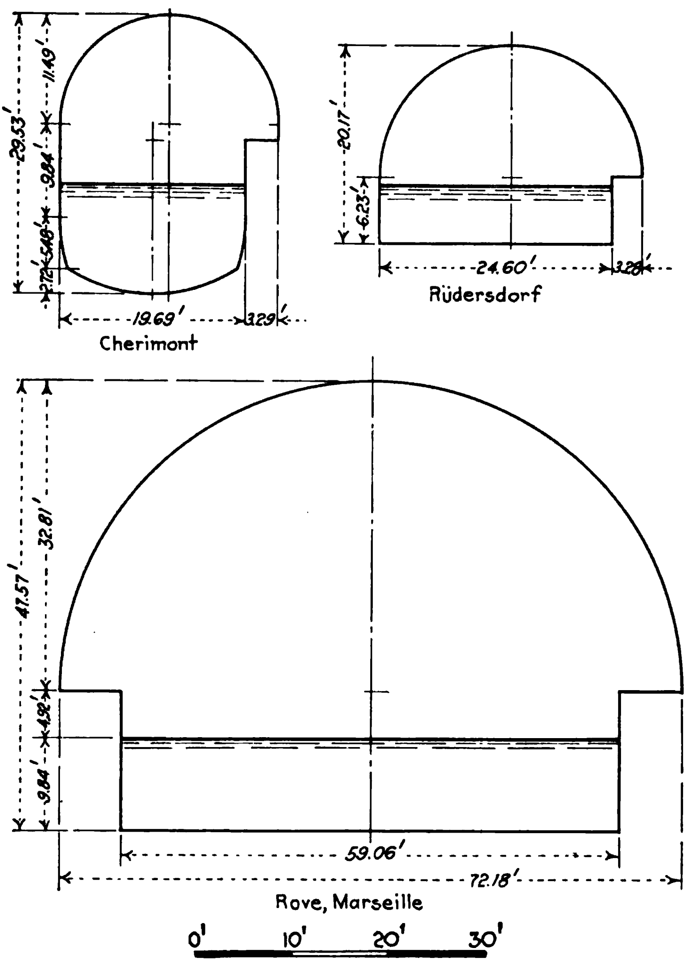


FIG. 19.—Cross sections of canal tunnels.

construction. In the following only shield driven tunnels will be considered.

14. External Cross-section of Shield Driven Tunnels.—The external cross-section of the greater number of existing shield

driven tunnels is circular. The principal advantage of that cross-section is that all the units of which the lining is built up have the same curvature and are largely interchangeable. It also permits breaking of the radial joints between adjacent rings of the lining, which adds greatly to the stiffness of the structure.

15. Rolling of the Shield.—Another advantage of the circular cross-section is that it is not affected by the rolling of the shield. When a shield is pushed forward it has a tendency to roll or turn around its own axis, and if this tendency is not checked, the shield will be turned gradually out of its upright position. This makes the work in the shield inconvenient, because the working platforms and partitions are slanting, but it does not otherwise affect the construction of the tunnel, if the shield and the lining have a circular cross-section. If, on the other hand, the shield and the lining have any other shape, it is evident that any rolling of the shield would have a serious effect on the construction of the tunnel. The rolling of the shield, therefore, is the common argument in favor of a circular tunnel lining for a shield driven tunnel. The argument does not appear, however, to be entirely conclusive. Experience has shown that a circular shield will roll, but very little experience has been had with shields of other shapes. The tendency of a circular shield to rolling is resisted only by the friction of the ground against the skin of the shield, and this friction is easily overcome by the jack pressures. The circular shield may roll without displacing the ground. If the shield has any other shape, however, it cannot roll without displacing the ground and it would appear that the resistance to displacement of the ground would be enough to prevent rolling. In this connection Greathead has stated (*Proc. Inst. C. E.*, vol. 123, p. 107): "In reference to the shape of tunnels, I maintain my opinion that for an iron tunnel the circular section was preferable to any other, under most conditions. Local requirements might necessitate a departure from that section, as in the case of a tunnel recently constructed by me in Dublin, or in soft silt and similar strata it might be advisable to adopt an oval section and in such case there would not be the difficulty Mr. Moir apprehended in carrying out that section with a shield . . ." In fact, several shield driven tunnels have been built successfully of other than circular cross-sections and it is worth recording that the largest tunnel which has yet been built by the aid of a shield of modern type, the Elm tunnel (*G*-10), is of a horseshoe shape.

Under any circumstances the rolling of a shield may be checked readily by proper precautions taken as soon as the tendency to roll becomes manifest. To prevent or reduce rolling, a projecting fin, or "plough," has been attached to the outer surface of the skin of some shields, particularly in London Clay, as a bilge keel is attached to a ship's hull.

16. Selection of Cross-section.—Neither the rolling of the shield nor any other feature connected with the driving of the shield will stand in the way of selecting a non-circular shape for the tunnel cross-section. It should be borne in mind, however, that when the lining is made of metal or masonry in prepared segments, the circular cross-section has the definite advantage of the segments being interchangeable to a larger degree than in other cross-sections, and this facilitates the erection. Consequently, where from the point of efficiency and economy there is equal choice, the circular cross-section is preferable.

17. Cross-section in Firm Ground.—From the discussion of stresses in Chap. VII the conclusion may be drawn that in firm ground within limits determined by the local conditions the cross-section may be elliptical with the major axis vertical, circular or elliptical with the major axis horizontal, with equal economy of lining materials. This condition makes it possible to select a shape best suited for the desired internal clearance.

18. Large Tunnels in Open Waterbearing Ground.—Perhaps the greatest importance of this condition is in connection with driving large tunnels through open waterbearing ground, in which every additional foot in vertical dimension adds greatly to the difficulty of construction, owing to the unbalanced external pressure on the face. An elliptical cross-section with the major axis horizontal will often permit the same internal traffic capacity with less height than required by a circular cross-section.

19. Construction Clearance.—When a shield is driven forward it is not possible to keep it on the true center line or gradient. With careful and skilled work the deviations may be kept within reasonable limits, but under any circumstances they may be large enough to affect the internal clearance of the tunnel. This may not be so important for some purposes, as for example when the tunnel is to be used for carrying water. In that case the slight deviations will not affect appreciably the flow. If the tunnel is to be used for a railroad, however, the deviations may make it impossible to carry the track alignment through with the proper

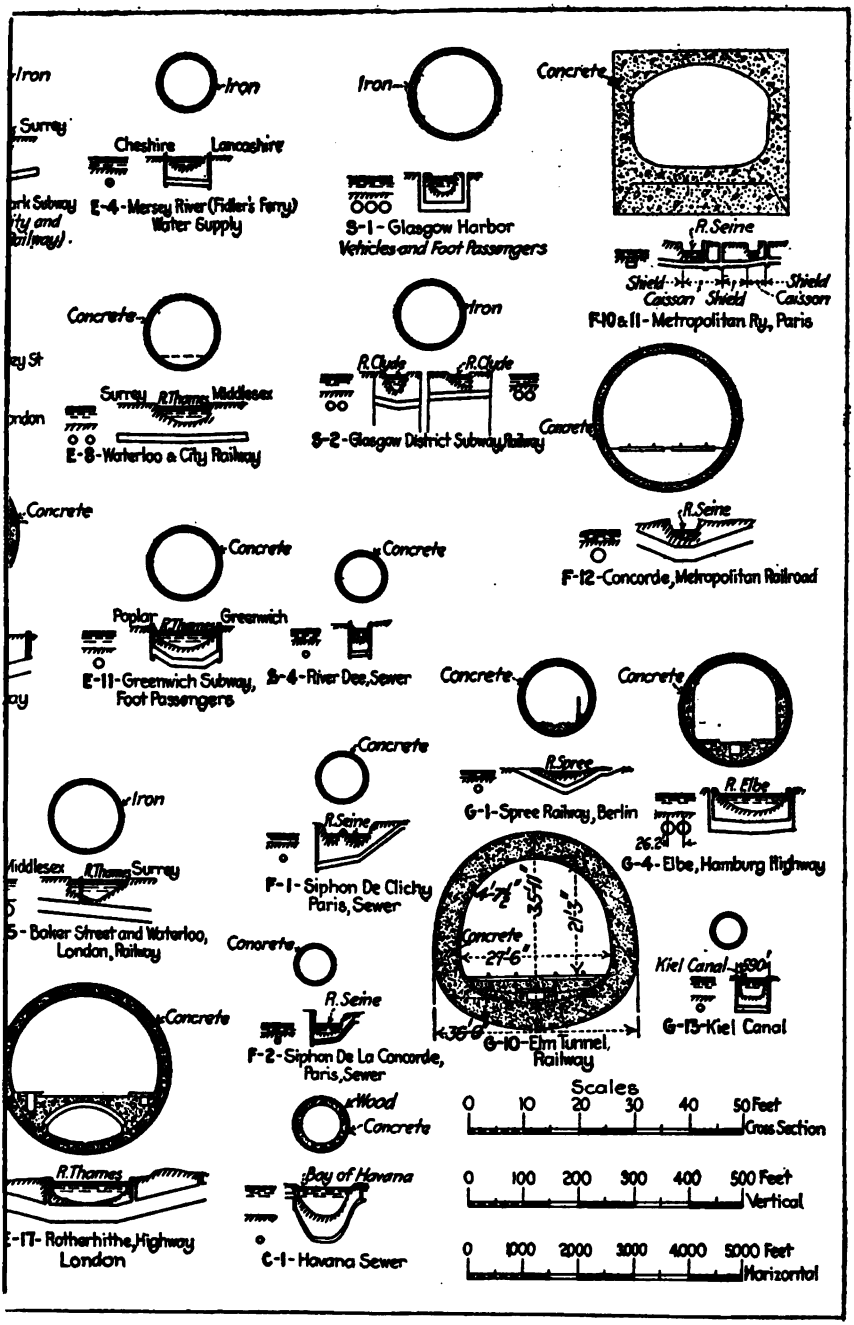
5

clearance. For that reason it is advisable in such cases to add to the internal clearance from 3 to 6 in. to allow for the deviations. If a neat interior appearance is desired, as for example in a highway tunnel, a similar allowance should be made.

20. Effect of Lining Material on External Cross-section.—The internal clearance is determined by the use of the tunnel and is independent of the material of which the lining is constructed. The thickness of the lining, and consequently the external cross-section, on the other hand, is affected by the lining material used. This should be taken into account in the consideration of the material to be selected.

21. Sub-division of Traffic.—In many cases the traffic through a tunnel may be sub-divided so that there is a choice of using either one large or two or more smaller tunnels. As a general rule it may be stated that if the choice is equal the smaller units will be the more economical.

22. Cross-section and Profile of Existing Tunnels.—Figure 20 shows the cross-section of several existing tunnels driven by shield under waterways. The profile of each tunnel is also shown to afford an index of comparison between the different works.



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CHAPTER VI

PRACTICAL MATTERS OF DESIGN

A. LOCATION, ALIGNMENT AND GRADIENTS

1. Character of Ground.—The type of tunnel to be used in any particular case is governed by the character of the ground in which it is to be built. The character of the ground must be known, therefore, before the design can be commenced. It may be determined by surface inspection, by consulting geological maps or a geologist, and by borings.

2. Borings.—Borings should be made, not only close to the proposed centerline, but also for several hundred feet on each side of this line. When the local conditions permit some freedom in the location of the center line, such borings may disclose a better location. In waterbearing ground the borings should not be made immediately above the proposed tunnel location, because they may become sources of blows during construction.

3. Parallel Tunnels.—If the structure is to consist of two or more shield driven tunnels parallel to each other, they should be spaced so far apart that the disturbances caused in the ground by the construction of one tunnel shall not affect the other. This is of special importance in ground of the character of Hudson River silt. In such ground the driving of one tunnel near another already built will cause the latter to distort and to move bodily away from that being driven. In open ground two tunnels driven close together may cause a heavy leakage of air from one tunnel to the other, unless the air pressure is the same in the two tunnels. This leakage can be avoided largely, however, by placing the locks in the two tunnels on the same transverse plane and keeping the adjacent portions of the tunnels under the same air pressure.

4. Alignment.—If possible, a shield driven tunnel should be on a tangent throughout. Driving around a curve greatly increases the cost of construction. If curves are unavoidable they should be made with as large a radius as the conditions will permit.

5. Maximum Gradient.—The maximum gradient permissible in a tunnel is fixed by the special purpose of the tunnel. In a

railroad tunnel it will be that which is standard for the railroad for equipment of the kind used in the tunnel. In the New York tunnels of the Pennsylvania Railroad, where electric locomotives are used a 2 per cent gradient was the maximum permitted. On the rapid transit railroads in New York with a multiple system of motor driven cars the maximum gradient permitted is 4.25 per cent. In highway tunnels the maximum gradient will be the same as that used in the locality on streets or bridge approaches with the same kind of paving as used in the tunnel.

6. Minimum Gradient.—No part of a tunnel should be built on a level gradient, because it interferes with the proper drainage. Experience indicates that a gradient of 0.25 per cent is the least that should be used and that one of 0.5 per cent is better.

7. Vertical Curves.—At the intersection of gradients, vertical curves should be introduced. They must not be forgotten even in the preliminary lay-out, because they affect often the elevations at the critical points of the profile as well as the gradients and the length of the tunnel. Horizontal and vertical curves should not overlap. Such an overlap increases the difficulty of steering the shield and are bad for the operation of a railroad.

8. Gradients in Simple Figures.—In order to facilitate the direction of the work of construction, the gradients should be laid out so that they are expressed in simple figures. For example, a gradient should be 1.5 per cent rather than 1.4932 per cent. Such a gradient gives the survey corps unnecessary work at a time when working under a heavy strain.

9. Depth of Tunnel.—Generally speaking a tunnel should be located at no greater depth than the conditions require. If there are other previous subsurface structures on the line of the tunnel, this may have to be placed deep enough to avoid them, or the subsurface structures may be relocated. If the tunnel is to pass under a waterway, the top of the tunnel must be kept some distance below the bed of the waterway. If the waterway may be subject to future deepening, this must be considered in locating the tunnel. In special cases the cover over the tunnel may be increased by artificially raising the bed of the waterway. This is done in the form of a "clay blanket," which may be removed after the tunnel is completed.

10. Shafts.—Shield driven tunnels are usually started from shafts. These should be located on the surface so as to provide the most convenient facilities for receiving materials of construc-

tion and disposing of the excavated spoil. Close proximity to waterfront or railroad or both is desirable. In dry ground the shaft may be either on or off the center line of the tunnel. In the latter case access to the tunnel is provided by cross headings. When a tunnel is to cross a waterway it is frequently possible to locate the shafts some distance from the waterway in dry ground. This decreases the cost of the shafts. If rock, for example, is encountered for some distance before the waterbearing ground is met, the tunnel may be driven without shield until near the waterbearing ground. An enlargement, or "shield chamber" may then be constructed in the rock tunnel at this point and the shield erected in this enlargement. The shield chamber should be large enough to allow ample room for the erection of the shield. In waterbearing ground the shaft should be on the center line of the tunnel and so large that the shield may be started from within the shaft. The shaft in that case will be a caisson sunk under air pressure and kept under air pressure until the shield has advanced sufficiently to permit the erection of a bulkhead in the tunnel.

B. LINING

11. Choice of Lining Material.—The choice of lining material should be determined by (*a*) the purpose of the tunnel; (*b*) the size of the tunnel; (*c*) the character of the ground and (*d*) the economy of construction. In connection with economy, it should be remembered that some lining materials, as concrete, may cost less per linear foot than others, as cast iron, but that a greater volume of excavation may be required.

12. Vertical Dimension of Tunnel.—In selecting the lining material and the shape of the tunnel it should be borne in mind that in waterbearing ground, and especially when the tunnel is large, the difficulty and cost of construction increase rapidly with the vertical dimension of the tunnel. Therefore, it is advisable to consider means of keeping this as small as the conditions will permit.

13. Construction Clearance.—In designing the cross-section of a tunnel, an allowance should be made for construction deviations from the proper line and gradient. Frequently various service appurtenances are carried through the tunnel. These should not be permitted to encroach on the construction clearance.

14. Construction Stresses.—In designing the lining the construction stresses as well as the permanent stresses should be considered. If the characteristics of the ground are different when subject to the disturbances caused by the driving of the tunnel from those which will exist in the undisturbed ground or when the ground has recovered from the disturbances, this should be taken into account. The effect of air pressure should be investigated. The lining must be able to carry·the pressure of the shield jacks. Some of the construction stresses are of short duration. High unit stresses are permissible in such cases.

15. Concrete Lining.—Avoid as much as possible reinforcement of concrete lining. Consider whether it would be more economical to increase the thickness of the concrete so as to dispense with reinforcement. Avoid all unnecessary recesses or complicated shapes, especially such as are made for saving concrete. Usually the saving in concrete is small compared to the additional cost of construction.

16. Steel Work.—Let no steel forming part of the structure be exposed, but cover it with concrete.

17. Segmental Lining.—Where the lining is made of previously prepared segments, as for example cast iron lining, make as few preperns as possible and make these so that each pattern is readily recognized. Make the length of the key piece so that all the segments can be swung into place. Provide special taper rings for going round curves or for correcting deviations.

C. INTERIOR FINISH

18. Railroad Track.—Frequently a ballasted track is used in tunnels. The advantages of such a track are easy riding and standard methods of maintenance. The main objection to the ballasted track is the difficulty in keeping it clean and sanitary. Spittle, discarded eatables, etc. deposited on the ballast decay and are breeding places for vermin. These matters with other debris thrown from the trains lodge in the ballast and are difficult to remove.

19. Concrete Track.—For this reason concrete track structures are frequently used in tunnels. Such tracks should be designed so that the ties may be removed and replaced within the confined space in the tunnel.

20. Stations.—Stations in railroad tunnels should be designed with sufficient platform space, both in width and in length,

to take care of present and future traffic. The exits from the platforms should not be at one end only.

21. Highway Tunnels.—The width of the roadway and its minimum clear height should be guided by local usage, keeping in mind possible future developments. One or two footwalks should be provided, where the vehicular traffic is heavy, for policing, maintenance, etc.

22. Roadway.—Unless the conditions invite it, there is no occasion to follow in a tunnel the usual design of a roadway with a crown at the center and gutters at the side. For a single track roadway, the best arrangement is usually to have the low point at the center, so that the drainage can be led directly to the main drain, which should be at the lowest point of the tunnel cross-section. For a double track roadway, this construction can be repeated for each track, making high points at the center and at the curbs. This arrangement would tend to keep the two lines of traffic guided along their proper course. The curb should be below the hub of the cars passing through the tunnel. If a single track of street railroad is carried through a tunnel of sufficient width for two lines of traffic, the track should be placed along the one side of the roadway.

23. Pavement of Roadway.—The pavement of the roadway should be as noiseless as possible and should be easy to replace. At the present time concrete, asphalt or wood block pavement answer these requirements. Future development may produce other materials suitable for the purpose.

24. Ventilation.—The question of whether artificial ventilation is required should be considered, and if fresh and foul air ducts are needed through the tunnel, the space they will occupy should be taken into account in determining the size of the tunnel.

25. Duct Lines.—Duct lines for cables are frequently carried through tunnels enclosed in the internal concrete structure. They must not be placed, however, in the area of the lining cross section assumed to be solid in the stress computations. They may be placed in space otherwise of no use and yet integral with the working section of the lining. The number of ducts that may be carried is usually limited by the facilities for providing room for drawing and splicing the cables rather than by the space available for the ducts. The designer should investigate the size of manholes required and their proper distance apart.

26. Water Pipe.—In most tunnels one or more water pipes should be installed for cleaning and fire fighting purposes. The size of the pipe will depend on the size and length of the tunnel and on the pressure of the water. Valves with hose connections should be placed on the line at frequent intervals. The pipes should be accessible to repairs. They should not, therefore, be buried in the concrete structure, making the locating and repair of a simple leak a difficult and expensive matter.

27. Drainage.—In tunnels built for purposes other than to carry water an efficient drainage system should be installed. Even though the tunnel may be practically watertight, some seepage may occur, the tunnel may be flushed with water for cleaning or to extinguish a fire, or the tunnel may be flooded. The drainage system will consist of drains throughout the tunnel, sumps at intervals, pumps at the sumps and discharge pipes from the pumps to the shaft.

28. Drains.—The drains should be placed at the lowest point of the tunnel cross-section and should have sufficient fall to insure drainage. They should be provided with manholes or hand holes at frequent intervals so that they may be cleaned easily. The seepage water into a tunnel frequently is charged with minerals which will deposit in the drains.

29. Sumps.—Sumps should be provided at the lowest point of the tunnel profile and at the ends of the tunnel. If the tunnel is long intermediate sumps may be advisable. The sumps are formed by sinking a small shaft from the bottom of the tunnel. The sumps at the ends of the tunnel are for the purpose of intercepting water from burst water mains, flooded sewers, etc., which may find its way into the tunnel from the shafts or approaches. In tunnels under a waterway it may be advisable to place sumps near the shore lines to prevent the low part of the tunnel from being completely flooded in case of a sudden inflow of water. Intercepting sumps should have a capacity of, say, 50,000 gal. to be able to take care of the water until the emergency pumping plant has started to operate.

30. Discharge Pipes.—The discharge pipes should be ample in size and should be accessible for repairs.

31. Pumps.—It is usually advisable to provide a small automatic pump of a capacity of about 50 gal. per minute to take care of the ordinary drainage and another pumping plant, of say, 1,000 gal. capacity to be used in an emergency. The latter

may be in one or more units. Standardized units throughout the tunnel structure are advisable.

32. Lighting.—The electric lighting of a tunnel should be arranged so that the lights as well as the light conduits are protected from injury, especially from wrecks or other accidents in the tunnel. It is in such cases that it is important that the lighting is uninterrupted. Unless two independent sources of electric lighting are installed, it may be advisable to provide oil lamps at intervals through the tunnel.

CHAPTER VII

STRESSES IN TUNNEL LININGS

A. INTRODUCTION

1. Proportioning by Judgment.—Owing to the uncertainty as to the magnitude of the external earth pressures the stresses in tunnel linings rarely have been determined by rational methods; experience and judgment have usually determined the design. When the first cast iron linings were proportioned the experience gained from masonry structures and from cast iron shaft linings was probably used. Later tunnel linings were proportioned in accordance with those already built, due consideration being given to changes in the size of the tunnel and in the character of the ground through which the tunnel was to be driven.

2. Limitations of Method.—This method of determining the dimensions of the lining is safe, but not necessarily economical, as long as the lining to be designed is of a size within the limits of those already built and when the ground in which it is to be used is similar to that in which such tunnels have been driven previously. If, however, the tunnel is larger or the ground different, the proper dimensioning becomes more uncertain.

3. Uncertain Economy of Method.—It is equally bad to make the dimensions either too heavy or too light. In the first case the cost of the structure is greater than necessary and in the other case, either the lining fails or the cost of construction becomes unnecessarily great. It is not always a proof that the lining is strong enough if it does not collapse. It is generally possible to support a weak lining with struts or tie-rods until an inner lining can be placed or until the stress conditions, which are often more severe at the time of initial erection than thereafter, have had time to readjust themselves, but the cost of this temporary work may be greater than would have been the additional cost of a lining of sufficient strength.

4. Proportioning by Computation.—In the following pages a method of determining the stresses along rational lines is developed. It involves the determination first, of, the external forces; and second, of the stresses produced in the tunnel lining by these

forces. Where the uncertainties of the earth pressures have not permitted a definite value to be assigned, limiting values of the pressures have been used. The tunnel lining has been treated as a statically indeterminate structure and the stresses have been determined accordingly. With the stresses determined, the proportioning of the dimensions of the lining follows.

B. EXTERNAL LOADINGS

5. Dead and Live Loads.—In a shield-driven tunnel the structure that supports the external forces is the lining. The weight of the lining is the dead load of the structure. The live load is partly inside and partly outside of the lining. The inside live load is the weight of the traffic that passes through the tunnel; it has generally only little effect on the stresses in the lining. The outside live load is the pressure of the surrounding ground, acting on every part of the external surface of the tunnel lining.

6. Uncertainties of Earth Pressures.—If the earth pressures were known the stresses in the lining might be obtained readily. There are, however, some doubts and differences of opinion as to these pressures which with our present knowledge makes it impossible to assign definite values to them. These uncertainties will now be considered.

7. Arching across Excavation.—It is known that most kinds of ground have a tendency to arch across a tunnel excavation and thereby to relieve the tunnel roof from carrying part of the superimposed load. If the tunnel lining were in close contact with the surrounding ground and the conditions existing prior to excavation were reestablished, no arching would exist and the vertical loading on the tunnel would be the weight of the superimposed earth and water. It is proposed to neglect the arching effect because, first, in certain kinds of ground the effect is small, particularly when the depth of the superimposed ground is only a few feet, as is often the case in shield driven tunnels, and second, without the arching effect the calculated stresses in the lining would be greater than if it were taken into account.

8. Horizontal Components of Earth Pressures in Dry Ground. The value of the horizontal components of the earth pressures is doubtful. The theories of earth pressures deal with dry granular masses without cohesion. The earth met in driving tunnels rarely resembles that assumed in such theories. There

are, however, certain characteristics about which a reasonable agreement exists. It is generally accepted that in dry ground the active horizontal earth pressure at any given depth is equal to the weight of the superimposed load multiplied by a constant which will be called c. If the material surrounding the tunnel is not a fluid, c will be less than 1. It is also generally accepted that a material for which c is less than 1 may, if called upon, produce a passive resistance of any value needed up to that of the weight of the superimposed load multiplied by $1/c$. In any ground, therefore, in which the active horizontal pressures are not sufficiently large in relation to the vertical pressures, the tunnel will have a tendency to deflect horizontally, but this tendency will be resisted immediately by the passive horizontal earth resistances. The passive horizontal earth resistances, therefore, function to resist a change of shape of the lining or, in other words, to prevent or reduce the bending stresses.

9. Horizontal Pressures in Waterbearing Ground.—In waterbearing ground the horizontal pressures will be affected by the water in the ground. The maximum active pressure that can be developed is that of the total head of the water plus the weight of the ground (as modified by being immersed in water) multiplied by the constant c. It is probable that the actual active pressure is less, when c is less than 1, but in the following this greater pressure is assumed, because the stresses calculated under this assumption are more severe than those which would obtain if a less value were used. The corresponding resistance to motion that the ground may be assumed to develop is that of the total head of water plus the weight of the ground (as modified by being immersed in water) multiplied by the value of $1/c$.

10. Value of c.—It is usually accepted that the constant c may be expressed by

$$c = \frac{1 - \sin \alpha}{1 + \sin \alpha} \tag{1}$$

where α is the angle of repose of the ground. In dry ground α is greater than 30 deg. Assuming this value for α, c will be equal to $\frac{1}{3}$, and this value of c is used in the following discussion for dry ground. In firm waterbearing ground, the minimum value of α is taken to be 19 deg., making c equal to 0.50. In flowing soft ground the value of c approaches 1.

11. Upward Vertical Forces.—When it is accepted that the downward pressures on the upper half of the tunnel are equal to

the weight of the superimposed loading, then the upward reaction must be equal to this weight plus the weight of the tunnel and its contents. If the downward load just balances the active upward pressure of the ground, no passive vertical resistances will be developed. If the downward load is greater, then sufficient passive pressure will develop to produce equilibrium, but the distribution is not known. It has been assumed here that the upward pressure, whether active or passive, less the weight of the lower half of the tunnel lining and the contents of the tunnel, is distributed uniformly over the horizontal diameter, because such a distribution would be reasonable and would produce more severe stresses than other distributions that reasonably could be assumed. If the active upward pressures are greater than the downward loads, then either the tunnel will rise or a downward passive resistance will be developed in the ground above the top of the tunnel. This condition will exist only when the ground approaches in character that of a fluid. In this case it may not be safe to rely on the passive resistance above the top of the tunnel, particularly when the cover is thin. When the tunnel rises, part of the active upward pressure is spent in moving the tunnel, and the problem is no longer static. For simplicity, however, so that it may be treated statically, it has also been assumed in this case that the upward pressure is such that it is balanced by the downward load.

12. Local Pressure on Lining.—Slides of earth may produce local loadings on the tunnel lining which cannot be predetermined. In a tunnel driven through soft ground the shield leaves a narrow annular space between the lining and the excavation. If the ground is very soft, experience has shown that it closes immediately and uniformly around the lining, filling the space. In stiffer ground good practice in construction requires that the space be filled immediately with some material so as to leave no voids outside of the lining. Methods exist, as described in Chap. XIII, by which the voids may be filled effectively. If they are filled, the chance of a slide is remote.

13. Summary.—The external forces may now be summed up as follows. (See Fig. 21.)

(1) The weight of the lining of the upper half of the tunnel, marked (1).
(2) The weight of the earth within the area marked (2).
(3) An upward force, marked (3), balancing (1) and (2) and distributed uniformly over the horizontal diameter.

(4) The weight of the loading above the top of the tunnel, marked (4).

(5) An upward reaction, marked (5), balancing (4) and distributed uniformly over the horizontal diameter.

(6) The horizontal pressure due to the water above the top of the tunnel, marked (6). This pressure is uniform from top to bottom and its intensity is equal to the weight of the water above the top of the tunnel.

(7) The horizontal pressure due to the water from top to bottom of the tunnel, marked (7). The intensity of this pressure at any point is equal to the weight of the water above this point measured vertically to the top of the tunnel.

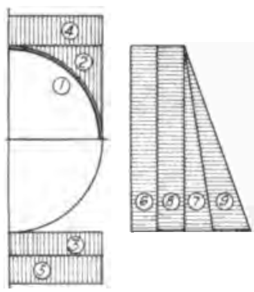

FIG. 21.—The permanent external forces which act upon a tunnel lining.

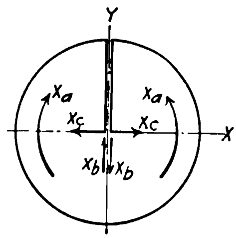

FIG. 22.

(8) The horizontal pressure due to the earth above the top of the tunnel, marked (8). This pressure is uniform from top to bottom and its intensity is equal to the weight of the earth (if in water as weighed in water) above the top of the tunnel, multiplied by a factor k which is greater than c and less than $1/c$.

(9) The horizontal pressure due to the earth between the top and bottom of the tunnel, marked (9). The intensity of this pressure at any point is equal to the weight of the earth (if in water as weighed in water) above this point measured vertically to the top of the tunnel, multiplied by the same factor k.

C. STRESSES IN AN ELASTIC ELLIPTICAL RING

14. Equations for Moments and Thrusts.—In Fig. 22 let the curve represent an elliptical ring with a uniform cross-section and select the system of coordinates as shown. Cut the ring at the top and introduce the unknown moments and forces X_a, X_b and X_c as shown, required to establish the conditions existing prior to the cut. In the cut ring, let M_o represent the moment for the external loading and M_a, M_b and M_c the moments for the load-

ings $X_a = -1$, $X_b = -1$ and $X_c = -1$, respectively, then the three unknowns may be determined by

$$\left.\begin{aligned}
0 &= \int M_oM_a ds - X_a\int M_a^2 ds - X_b\int M_aM_b ds \\
&\qquad - X_c\int M_aM_c ds \\
0 &= \int M_oM_b ds - X_a\int M_aM_b ds - X_b\int M_b^2 ds \\
&\qquad - X_c\int M_bM_c ds \\
0 &= \int M_oM_c ds - X_a\int M_aM_c ds - X_b\int M_bM_c ds \\
&\qquad - X_c\int M_c^2 ds
\end{aligned}\right\} \qquad (2)$$

On account of the symmetry

$\int M_aM_b ds = 0$, $\int M_aM_c ds = 0$, $\int M_bM_c ds = 0$ and $\int M_oM_b ds = 0$

so that the equations (2) may be written

$$\begin{aligned}
0 &= \int M_oM_a ds - X_a\int M_a^2 ds \\
0 &= \qquad\qquad\quad - X_b\int M_b^2 ds \\
0 &= \int M_oM_c ds - X_c\int M_c^2 ds
\end{aligned}$$

or

$$\left.\begin{aligned}
X_a &= \frac{\int M_oM_a ds}{\int M_a^2 ds} \\
X_b &= 0 \\
X_c &= \frac{\int M_oM_c ds}{\int M_c^2 ds}
\end{aligned}\right\} \qquad (3)$$

The moment at any given point in the uncut ring may be expressed by

$$M = M_o - X_a - X_b x - X_c y \qquad (4)$$

and the thrust by

$$N = N_o + X_b \sin\vartheta - X_c \cos\vartheta \qquad (5)$$

where N_o represents the thrust in the cut ring.

Applying equations (3) the equations (4) and (5) will read

$$M = M_o - \frac{\int M_oM_a ds}{\int M_a^2 ds} - y\frac{\int M_oM_c ds}{\int M_c^2 ds} \qquad (6)$$

and

$$N = N_o - \frac{\int M_oM_c ds}{\int M_c^2 ds}\cos\vartheta \qquad (7)$$

For any given point $M_a = 1$ and $M_c = y$;

Therefore by inserting these values in (6) and (7) these equations will read

$$M = M_o - \frac{\int M_o ds}{\int ds} - y\frac{\int M_o y ds}{\int y^2 ds} \qquad (8)$$

$$N = N_o - \frac{\int M_o y ds}{\int M^2{}_c{}^2 ds}\cos\vartheta \qquad (9)$$

in which $\int ds = s$ represents the length of the circumference of the ellipse. The integrations cover the whole ellipse. In the following the moments are positive when producing tension at inside of ring. Direct tension stresses are positive, compression stresses negative.

15. Method of Application.—In determining the moments and thrusts due to the external loadings each item of loading as enumerated in par. **13** is treated separately and then summed up. For a circular ring the necessary integrations are carried out readily, but for an ellipse the expressions are not directly integratable. In that case they may be determined by summation.

16. Example of Integration.—Determine the moment in a circular ring for loading (7) par. **13**. The weight of the water is w_1 per cubic foot and the radius of the ring is r. (See Fig. 23.)

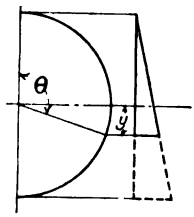

FIG. 23.

$$M_o = -\tfrac{1}{6}w_1(r-y)^3 = -\tfrac{1}{6}w_1r^3(1-\cos\vartheta)^3$$

$$\int M_o ds = -\tfrac{1}{3}w_1r^4\int_0^\pi(1-\cos\vartheta)^3 d\vartheta = -\tfrac{5}{6}\pi w_1r^4$$

$$\int M_o y ds = -\tfrac{1}{3}w_1r^5\int_0^\pi \cos\vartheta\,(1-\cos\vartheta)^3 d\vartheta = \tfrac{5}{8}\pi w_1r^5$$

$$s = 2\pi r$$

$$\int y^2 ds = \pi r^3$$

and

$$M = M_o + \tfrac{5}{12}w_1r^3 - \tfrac{5}{8}w_1r^3\cos\vartheta$$

The moments at top, axis level and bottom, respectively, are

$$M_1 = 0 + \tfrac{5}{12}w_1r^3 - \tfrac{5}{8}w_1r^3 = -\tfrac{5}{24}w_1r^3$$

$$M_2 = -\tfrac{1}{6}w_1r^3 + \tfrac{5}{12}w_1r^3 = +\tfrac{1}{4}w_1r^3$$

$$M_3 = -\tfrac{4}{3}w_1r^3 + \tfrac{5}{12}w_1r^3 + \tfrac{5}{8}w_1r^3 = -\tfrac{7}{24}w_1r^3$$

17. Deflection of an Elastic Ring.—The deflection of an elastic ring may be measured by the shortening of the vertical diameter. This shortening may be expressed by

$$\delta EI = \int MM'ds \qquad (10)$$

where δ is the deflection, E the modulus of elasticity of the material, I the moment of inertia of the cross-section of the ring wall, M the actual moment due to the loading considered and M^1 the moment in the cut ring due to a loading 1 at top and bottom.

D. MOMENTS AND THRUSTS

18. Symbols Used.—In the succeeding discussion the following symbols are used.

a = the horizontal external radius of the ellipse in feet.
a_1 = the horizontal radius of the neutral axis in feet.
b = the vertical external radius of the ellipse in feet.
w_1 = weight of water in pounds per cubic foot.
w_2 = weight of earth in pounds per cubic foot (if in water as weighed in water).
$w = w_1 + w_2$
W = weight of the tunnel lining in pounds per linear foot of tunnel.
P = vertical loading above the top of the tunnel in pounds per square foot.
Q = air pressure in tunnel above normal in pounds per square foot.
h_1 = depth of water above the surface of the ground in feet.
h_2 = depth of earth above top of tunnel in feet.
c = ratio of horizontal to vertical earth pressure (see pars. **8, 9** and **10**).
k = a factor which is greater than c and less than $1/c$.
n_1, n_2, n_3, n_4, n_5 = constants.
M_1 = moment at top of tunnel.
M_2 = moment at horizontal axis level of tunnel.
M_3 = moment at bottom of tunnel.
N_1 = thrust at top of tunnel.
N_2 = thrust at horizontal axis level of tunnel.
N_3 = thrust at bottom of tunnel.

19. General Equation for Moments.—By applying the calculations of moments as developed in Section C of this chapter to the loadings as given in par. **13,** the following general equation is obtained for the moment of an elliptical tunnel lining.

$$M = ka_1(n_1w_2a^2 + n_2w_2h_2a) + n_1w_1a_1a^2 + n_2(w_1(h_1 + h_2) - Q)\,a_1a + n_3(w_1 + w_2)a_1a^2 + n_4Wa_1 + n_5(P - Q)a_1a \quad (11)$$

TABLE IV.—VALUES OF CONSTANTS n_1, n_2, n_3, n_4, n_5, IN EQUATION (11)

$\frac{b}{a}$	Moment at top M_1					Moment at axis level M_2					Moment at bottom M_3				
	n_1	n_2	n_3	n_4	n_5	n_1	n_2	n_3	n_4	n_5	n_1	n_2	n_3	n_4	n_5
0.70	−0.07	−0.11	0.02	0.05	0.23	0.09	0.13	−0.03	−0.06	−0.27	−0.09	−0.11	0.03	0.05	0.23
0.75	−0.08	−0.13	0.02	0.05	0.23	0.11	0.15	−0.03	−0.06	−0.26	−0.11	−0.13	0.03	0.05	0.23
0.80	−0.10	−0.15	0.02	0.05	0.24	0.13	0.17	−0.03	−0.06	−0.26	−0.14	−0.15	0.03	0.05	0.24
0.85	−0.12	−0.17	0.02	0.05	0.24	0.15	0.19	−0.04	−0.06	−0.26	−0.17	−0.17	0.04	0.06	0.24
0.90	−0.15	−0.19	0.02	0.05	0.25	0.18	0.21	−0.04	−0.06	−0.26	−0.21	−0.19	0.04	0.06	0.25
0.95	−0.18	−0.22	0.02	0.05	0.25	0.21	0.23	−0.04	−0.06	−0.25	−0.25	−0.22	0.04	0.06	0.25
1.00	−0.21	−0.25	0.03	0.05	0.25	0.25	0.25	−0.04	−0.06	−0.25	−0.29	−0.25	0.04	0.06	0.25
1.05	−0.24	−0.28	0.03	0.05	0.25	0.30	0.27	−0.04	−0.05	−0.25	−0.34	−0.28	0.05	0.06	0.25
1.10	−0.27	−0.31	0.03	0.05	0.26	0.35	0.29	−0.04	−0.05	−0.24	−0.40	−0.31	0.05	0.06	0.26
1.15	−0.31	−0.34	0.03	0.05	0.26	0.40	0.31	−0.04	−0.05	−0.24	−0.45	−0.34	0.05	0.06	0.26
1.20	−0.35	−0.37	0.03	0.05	0.26	0.46	0.34	−0.04	−0.05	−0.24	−0.51	−0.37	0.06	0.06	0.26
1.25	−0.39	−0.41	0.04	0.05	0.26	0.52	0.37	−0.05	−0.05	−0.24	−0.57	−0.41	0.06	0.06	0.26
1.30	−0.44	−0.45	0.04	0.05	0.27	0.58	0.39	−0.05	−0.05	−0.23	−0.64	−0.45	0.06	0.06	0.27
1.35	−0.49	−0.49	0.04	0.05	0.27	0.64	0.42	−0.05	−0.05	−0.23	−0.71	−0.49	0.07	0.06	0.27
1.40	−0.54	−0.53	0.04	0.05	0.27	0.71	0.45	−0.05	−0.05	−0.23	−0.79	−0.53	0.07	0.07	0.27

The constants n_1, n_2, n_3, n_4, n_5 vary with the location of the point for which the moment is considered. Their values are given in Table IV for top, axis level and bottom points, respectively, for elliptical linings with the ratio of the vertical to the horizontal radius varying from 0.70 to 1.40. With these values of the constants the moments are expressed in foot-pounds.

20. Moments in Dry Ground.—For dry ground equation (11) may be written

$$M = ka_1(n_1w_2a^2 + n_2Pa) - n_2Qa_1a + n_3w_2a_1a^2 + n_4Wa_1 + n_5(P - Q)a_1a \qquad (12)$$

This moment will be zero when

$$k = -\frac{-n_2Qa + n_3w_2a^2 + n_4W + n_5(P-Q)a}{n_1w_2a^2 + n_2Pa} \qquad (13)$$

According to par. **18,** k is greater than c and less than $1/c$, and according to par. **10,** c may in dry ground be taken as 1/3. Consequently, if k as determined by (13) lies between the limits 1/3 and 3, the tunnel lining will not be subjected to a moment from the given loading.

21. Dead Load Moments.—The lining will be subject, however, to a moment due to its own weight. At the time of erection the lining is not supported by the surrounding ground and it will, therefore, receive an initial deflection due to its own weight. The moment caused by this deflection depends on the method of support. As a working condition the moment, expressed in inch-pounds may be assumed to be

$$M = 1.2Wa \qquad (14)$$

In a circular tunnel this would correspond to a support at two points at the bottom, 20 deg. distant from the bottom point.

22. Thrust in Dry Ground.—For the full loading the thrust may be determined by equation (9), but the following expressions, which ignore the effect of the internal stresses, are sufficiently approximate and more convenient for use.

$$\left.\begin{aligned} N_1 &= -bw_1(0.67b + h_1 + h_2) - kbw_2(0.67b + h_2) + Qb \\ N_2 &= -Pa - 0.22(w_1 + w_2)ab - 0.25W + Qa \\ N_3 &= -bw_1(1.33b + h_1 + h_2) - kbw_2(1.33b + h_2) + Qb \end{aligned}\right\} \qquad (15)$$

The thrust corresponding to the moment (14) is insignificant and may be assumed to be equal to zero.

23. Moments in Firm Waterbearing Ground.—In firm waterbearing ground apply equation (11). According to par. **10,** the

value of c may here be taken as 0.50, making $1/c = 2$. If k as determined by

$$k = \frac{n_1w_1a^2+n_2(w_1(h_1+h_2)-Q)a+n_3(w_1+w_2)a^2+n_4W+n_5(P-Q)a}{n_1w_2a^2 + n_2w_2h_2a} \tag{16}$$

lies between the limits 0.50 and 2.00, the moment will be zero. If k is less than 0.50 the value of $k = 0.50$ should be used in equation (11) and if k is greater than 2.00, this value should be used.

24. Dead Load Moments in Firm Waterbearing Ground.—As stated in par. **21,** the lining will be subjected to a moment due to the weight of the lining. If the moments as determined by equation (11) are less than that determined by equation (14), the latter moment should be used.

25. Thrust in Firm Waterbearing Ground.—The thrust in firm waterbearing ground may be determined by the equations (15).

26. Definition of Soft Ground.—By soft ground is understood in this connection ground which either temporarily or permanently approaches in character that of a fluid.

27. Hudson River Silt.—The silt underlying the Hudson River in the vicinity of New York City is an example of such ground. It may be described as an extremely finely divided dust, supersaturated with water. The fineness of the particles is so great that Portland cement in comparison is a coarse powder. During the construction of the Pennsylvania Railroad tunnels under the Hudson River (A-18) careful observations were made of the behavior of the tunnels in the silt. It was observed that from the time of erection of a ring of the cast iron lining and for a period of about two weeks thereafter the vertical diameter continued to increase, the average increase at the end of this period being 1.22 in. The external diameter of the tunnel was 23 ft. After this period the vertical diameter started to decrease, but at a much slower rate, and continued to do so for a period of about two and one-half years, when the ring had obtained a diameter of about one-eighth of an inch less than true. Observations were then discontinued, because the internal concrete lining was placed, but it is probable that the deformation had about ceased at that time. The action of the lining may be explained by the silt having in its undisturbed state a potential passive resistance which was temporarily destroyed by the violent disturbance of driving the shield through it. Immediately after

the passing of the shield the silt surrounding the tunnel, therefore, acted on the lining as a fluid. In course of time, however, the silt gradually returned to its original condition, whereby the horizontal pressure on the lining decreased, causing the lining to shorten its vertical diameter until sufficient passive resistance had been developed to make the bending moment in the lining approximately zero. This would occur when the vertical diameter had reached a length of slightly less than true.

28. Observed Elongation a Measure of *c*.—By determining the deflection according to equation (10), par. **17,** the following expression is obtained for the shortening of the vertical diameter in a circular lining with radius r under the loading as given in par. **13.**

$$\delta = \frac{r^3}{EI}((0.0254 - 0.1667c)wr^2 + 0.0357W$$
$$+ 0.1667\ (1 - c)(P - Q)r)$$

In the case of the Pennsylvania tunnels, $r = 11.5$; $w = 108$; $W = 12{,}200$; $P = 5{,}800$; $Q = 3{,}600$ and $I = 405$. The computed shortening of the vertical diameter for values of c ranging from 0.75 to 1.00 is shown in Fig. 24. It will be seen that for a value of $c = 0.76$ the vertical diameter will not change its length. For smaller values of c the diameter would shorten if it were not for the passive resistances preventing it, and for larger values of c the diameter will increase its length at a uniform rate until the maximum value of c (namely, 1) is reached, when the computed increase is 0.65 in. The observed increase was 1.22 in., so that for any value of c the computed change is less than observed. The reason for this is that stretching of the bolts, deflection of the flanges and play in the joints add to the deflection of the lining. The computed value nearest to that observed is that for $c = 1$. While it cannot be stated definitely that c had this value at the time of maximum elongation, it is indicated by the fact that the observed elongation was greater than that computed for $c = 1$. If c had been less than 1, passive resistances would have developed with the effect of preventing any material elongation of the vertical diameter. Under the

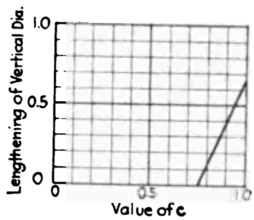

FIG. 24.—Relationship between c and shortening of vertical diameter for values of c between 0.75 and 1.00.

circumstances the probability of c being equal to 1 is sufficiently great to warrant the use of this value in the computations for tunnel linings in ground of this character.

29. Moments in Soft Ground.—For soft ground, therefore, the equation (11) should be used with k equal to 1. This equation may then be written

$$M = a_1(m_1wa^2 + m_2W + m_3(P - Q)a) \qquad (17)$$

where $m_1 = n_1 + n_3$, $m_2 = n_4$, $m_3 = n_2 + n_5$, $w = w_1 + w_2$. The values of the constants m_1, m_2, m_3 are shown in Table V.

TABLE V.—VALUES OF CONSTANTS m_1, m_2, m_3, IN EQUATION (17)

$\frac{b}{a}$	Moment at top, M_1			Moment at axis level M_2			Moment at bottom, M_3		
	m_1	m_2	m_3	m_1	m_2	m_3	m_1	m_2	m_3
0.70	−0.05	0.05	0.12	0.06	−0.06	−0.14	−0.06	0.05	0.12
0.75	−0.06	0.05	0.11	0.08	−0.06	−0.11	−0.08	0.05	0.11
0.80	−0.08	0.05	0.09	0.10	−0.06	−0.09	−0.11	0.05	0.09
0.85	−0.10	0.05	0.07	0.12	−0.06	−0.07	−0.14	0.06	0.07
0.90	−0.12	0.05	0.05	0.14	−0.06	−0.05	−0.17	0.06	0.05
0.95	−0.15	0.05	0.03	0.17	−0.06	−0.02	−0.21	0.06	0.03
1.00	−0.18	0.05	0.00	0.21	−0.06	0.00	−0.25	0.06	0.00

30. Economical Cross-section in Soft Ground.—A tunnel driven through soft ground of the character defined in par. **26** will be driven under air pressure, but as it is possible that during the driving the air pressure may be removed periodically, either by accident or on purpose, it is necessary to design the lining so that it is capable of carrying the stresses to which it may be subjected in either case. While a tunnel in this kind of ground usually is driven under an air pressure less than the water pressure at the top of the tunnel, there may be occasions when the pressure will have to be increased to one balancing the full external pressure of water and ground at or below axis level, and this is the air pressure that should be considered in the computations. With the latter air pressure no material reduction in the bending stresses is obtained by diverging from the circular cross-section, and this will usually be found most economical, except possibly when the tunnel is large; in this case elliptical cross-

sections with the major axis horizontal should also be investigated. Elliptical cross-sections with major axis vertical are always less economical than the circular cross-section.

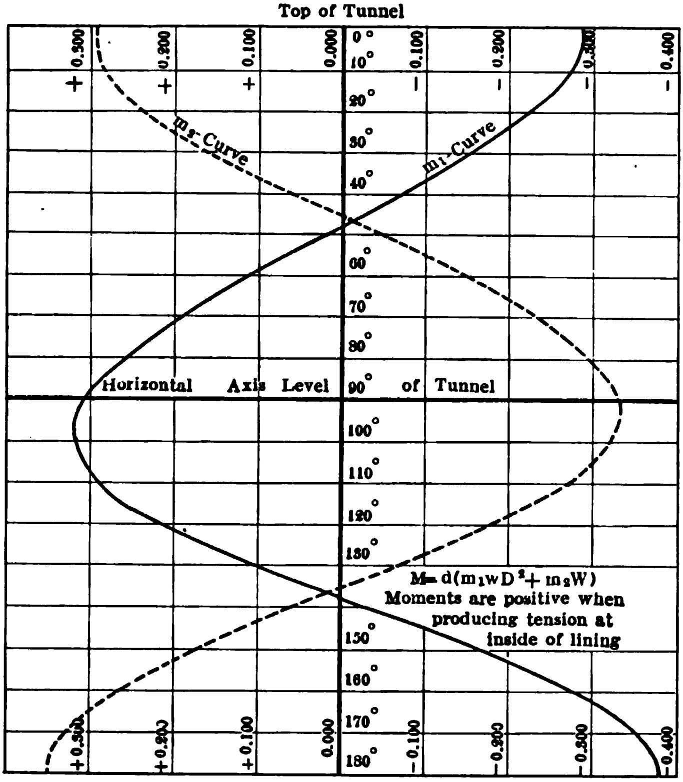

FIG. 25.—Values of constants m_1 and m_2 for all points of the circumference.

31. Moments in Circular Cross-section in Soft Ground.—If D represents the external diameter in feet of a circular tunnel lining and d the diameter of the neutral axis, then equation (17) may be written

$$M = d(m_1 w D^2 + m_2 W) \tag{18}$$

The values of the constants m_1 and m_2 are shown in Fig. 25 for all points of the circumference. With these constants, M is expressed in inch-pounds.

32. Thrusts in Circular Cross-section in Soft Ground.—The corresponding thrusts are expressed by the equation

$$N = n_1 wD^2 + n_2 W - \tfrac{1}{2}(P - Q)D \qquad (19)$$

The values of the constants n_1 and n_2 are shown in Fig. 26 for all points of the circumference.

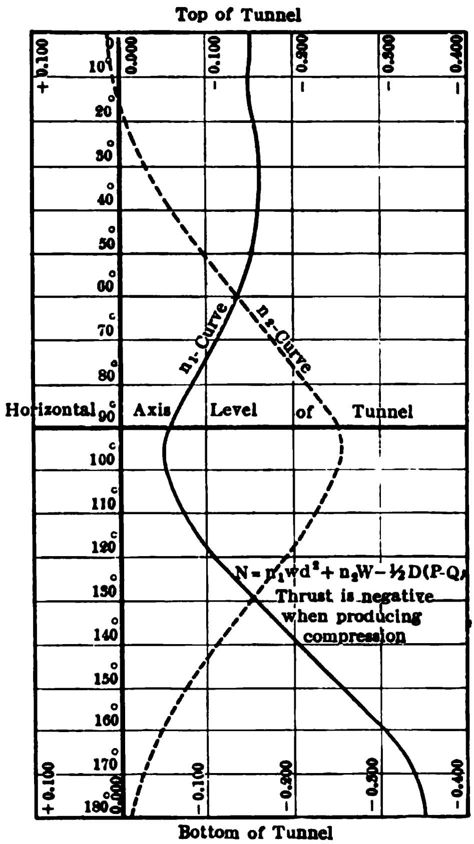

Fig. 26.—Values of constants n_1 and n_2 for all points of the circumference.

33. Summary.—The most suitable cross-section for a tunnel lining depends on the character of the ground, as follows.

In dry ground within certain limits the cross-section may be elliptical with the major axis vertical or horizontal, or it may be circular with equal economy.

In waterbearing firm ground the same conditions exist, but the limits are narrower; usually a cross-section in which the ratio of the vertical to the horizontal diameter ranges between 0.8 and 1.0 will be the most economical.

In soft ground the circular cross-section is usually the most economical, although for large tunnels it is advisable to investigate also elliptical cross-sections with the major axis horizontal.

E. STRESSES IN LINING

34. Computation of Stresses.—When the moments and thrusts are known the stresses in the lining may be determined by

$$s = N/A \pm M/S \tag{20}$$

where

s = unit stress in pounds per square inch.
N = thrust in pounds per linear foot of tunnel.
A = cross-section area of the wall of the lining in square inches per linear foot of tunnel.
M = moment in inch-pounds per linear foot of tunnel.
S = section modulus of the wall of the lining in inches cubed per linear foot of tunnel.

As previously stated, the moment is taken as positive when producing tension at the inside of the lining; direct tension stress is positive and compression negative.

35. Stresses during Construction in Dry Ground.—During construction the moment in the lining of a tunnel driven through dry ground is expressed by equation (14) and the corresponding thrust may, according to par. **22**, be assumed to be zero. If the work is carried out under compressed air the air pressure will not affect the thrust at the time of initial erection, because it will be present at the outside as well as at the inside of the lining. After the space behind the lining has been filled and the lining has been subjected to the external earth pressures the moment will be determined by equation (12), par. **20**, and the thrust by equation (15), par. **22**.

36. Permanent Stresses in Dry Ground.—The permanent moment in dry ground is determined by equation (12), par. **20**, in which $Q = 0$. The corresponding thrust is determined by equation (15), par. **22**, in which $Q = 0$.

37. Stresses during Construction in Firm Waterbearing Ground.—In firm waterbearing ground the initial moment is determined by equation (14), par. **21,** and the corresponding thrust is zero. When the earth pressures are acting the moment is determined by equation (11), par. **19,** and the thrust by equation (15), par. **22.**

38. Permanent Stresses in Firm Waterbearing Ground.—The permanent moment in firm waterbearing ground is determined by equation (11), par. **19,** and the corresponding thrust by equation (15), par. **22.** In both equations $Q = 0$.

39. Stresses during Construction in Soft Ground.—In soft ground the moment is determined during construction by equation (17), par. **29,** for elliptical cross-sections and by equation (18), par. **31,** for circular cross-sections. The thrust is determined by equation (5), par. **14,** for elliptical cross-sections and by equation (19) for circular cross-sections.

40. Permanent Stresses in Soft Ground.—If the active horizontal pressures decrease after the disturbance caused by the construction is past, then the moment is determined by equation (11) and the thrust by equation (15).

41. Concrete Lining.—The above moments and thrusts are based on the assumption that no internal support of the arch of the lining is provided. In concrete and other masonry linings an internal support must be provided until the lining is strong enough to carry the outside load and until the lining has received outside support, unless the lining has been designed to carry a moment as expressed by equation (11).

42. Wood Lining.—When the segments of a wood lining are properly fastened together, the individual segments are spliced through the adjacent rings. Each ring, therefore, must be assumed to carry the tension of two rings, while the compression is carried by the individual ring. See Chap. VIII, pars. 61 to 68.

43. Cast Iron Lining.—Cast iron lining has an unsymmetrical cross-section, and the neutral axis is nearest to the outside. Consequently, the section modulus is least on the inside. As the tensile strength of cast iron is less than its compressive strength, the strength of the lining is usually governed by the maximum tensile stress.

44. Steel Lining.—A lining of structural steel or of steel castings will also have an unsymmetrical cross-section, but the tensile strength is the same as the compressive strength, so that

the strength of the lining will be determined by the maximum stress, whether tensile or compressive.

F. APPLICATION TO EXISTING STRUCTURES

45. Cleveland New West Side Water Intake Tunnel (A-26). This tunnel is circular in shape, driven through firm waterbearing ground and lined with precast concrete block. The external radius is $a = 5.96$ ft.; the radius to the neutral axis is $a_1 = 5.48$ ft.; the weight of the lining is $W = 4{,}600$ lb. per linear foot of tunnel. Depth of water $h_1 = 25$ ft.; weight $w_1 = 62.5$ lb. per cubic foot. Depth of cover $h_2 = 15$ ft.; weight $w_2 =$ (in water) 65 lb. per cubic foot. From equation (16):

$$k = -\frac{2{,}220n_1 + 14{,}900n_2 + 4{,}530n_3 + 4{,}600n_4 + 20{,}700n_5}{2{,}310n_1 + 5{,}800n_2}$$

Inserting in this expression the values of the constants for the moment M_3 as given in Table IV.

$$k_3 = \frac{-2{,}220 \times 0.29 - 14{,}900 \times 0.25 + 4{,}530 \times 0.04 + 4{,}600 \times 0.06 + 20{,}700 \times 0.25}{2{,}310 \times 0.29 + 5{,}800 \times 0.25} = 0.60$$

This value of k is within the limits of 0.50 and 2.00 and the lining will, consequently, have no moment due to the entire loading. The moment, therefore, will be determined by equation (14):

$$M_3 = 1.2 \times 4{,}600 \times 5.96 = 33{,}000 \text{ in.-lb.}$$

This moment will not exist until the lining has received support from the surrounding ground, in which case the corresponding thrust is found by equation (15). The value to be inserted for k in this equation may be any between 0.5 and 2, and the latter value is used. The air pressure is taken at 20 lb. per square inch or $Q = 2{,}880$ lb.

$$N_3 = 5.96\,(-\,62.5(1.33 \times 5.96 + 25 + 15) - 2 \times 65\,(1.33 \times 5.96 + 15) + 2{,}880) = -18{,}200 \text{ lb./in.}^2$$

The area A of the lining is $11.5 \times 12 = 138$ sq. in. and the section modulus $S = 2 \times 11.5 \times 11.5 = 264.5$. According to equation (20) the stress is

$$s = -\frac{18{,}200}{138} \pm \frac{33{,}000}{264.5} = \begin{cases} -7 \text{ lb./in.}^2 \\ -257 \text{ lb./in.}^2 \end{cases}$$

With no air pressure $N = -\ 35{,}300$ lb. and the maximum compressive stress is

$$s = -381 \text{ lb./in.}^2$$

46. Dorchester (A-34).—Circular wood lined tunnel through firm waterbearing ground. $a = 12.08$ ft.; $a_1 = 11.71$ ft., $W = 2{,}800$ lb., $h_1 = 30$ ft., $h_2 = 20$ ft., $w_1 = 64$ lb., $w_2 = 65$ lb., $P = 4{,}500$ lb. By inserting these values in equation (16), k is found equal to 0.32. This value is less than 0.50, and the moment due to all the external forces is, therefore, determined by equation (11):

$$M_3 = 140.5(-0.50(2{,}750 + 3{,}920) - 2{,}710 - 9{,}660 + 750 + 170 + 13{,}590) = -168{,}000 \text{ in.-lb.}$$

The corresponding thrust is found from equation (15). If the air pressure is 25 lb. per square inch, then

$$N_3 = -\ 12.08(64 \times 66 + 0.50 \times 65 \times 36 - 3{,}600) = -\ 22{,}000 \text{ lb.}$$

Since, $A = 12 \times 9 = 108$ and $S = 2 \times 81 = 162$, then

$$s = -\frac{22{,}000}{108} \pm \frac{168{,}000}{162} = \begin{cases} +833 \text{ lb./in.}^2 \\ -1{,}241 \text{ lb./in.}^2 \end{cases}$$

The actual tensile stress is according to par. **42** twice that computed of $2 \times 833 = 1{,}666$ lb. per square inch.
When not subject to air pressure the thrust is 65,200 lb. and the maximum compressive stress is $-1{,}641$ lb. per square inch.

47. City & South London (E-10).—Circular cast iron lining in dry ground. $a = 5.62$ ft., $a_1 = 5.54$ ft., $W = 1{,}800$ lb., $h_2 = 80$ ft., $w_2 = 120$ lb. From equation (13) k is found equal to 0.95. According to par. **20,** with this value of k there will be no moment for the total external forces. The moment is, therefore, determined by equation (14) from which $M_3 = 12{,}200$ in.-lb. The thrust is zero and the section modulus is 6. The stress is therefore

$$s = \frac{12{,}200}{6} = +2{,}000 \text{ lb./in.}^2$$

The maximum compressive stress is according to equation (15), the area A being 14.1 sq. in.

$$s = -\frac{55{,}200}{14.1} = -3{,}900 \text{ lb./in.}^2$$

48. Whitehall (A-28).—Circular cast iron lining in firm waterbearing ground. $a = 9$ ft., $a_1 = 8.82$ ft., $W = 6{,}500$ lb., $h_1 = 40$ ft., $h_2 = 22$ ft.; $w_1 = 64$ lb., $w_2 = 60$ lb. According to equation (16), k is found equal to 0.51, and the moment is consequently determined by equation (14):

$$M_3 = 1.2 \times 6{,}500 \times 9 = 70{,}200 \text{ in.-lb.}$$

The thrust is zero and $S = 20.8$, consequently, the maximum tensile stress is

$$s = \frac{70{,}200}{20.8} = 3{,}370 \text{ lb./in.}^2$$

49. Pennsylvania Railroad Hudson River (A-18).—Circular cast iron lining in soft ground. The external diameter is 23 ft., the diameter to the neutral axis $d = 22.5$ ft. The weight of the lining is $W = 12{,}240$ lb. Top pressure $P = 5{,}800$ lb., air pressure $Q = 3{,}600$ lb., weight of ground $w = 108$ lb. Area of lining $A = 40.3$ sq. in., section modulus $S = 50.3$.
According to equation (18)

$$M_2 = 22.5(57{,}132m_1 - 12{,}240m_2)$$

From Fig. 25 the constants are at axis level $m_1 = 0.31$ and $m_2 = -0.33$; therefore

$$M_2 = 22.5(57{,}132 \times 0.31 - 12{,}240 \times 0.33) = 308{,}000 \text{ in.-lb.}$$

The corresponding thrust is found by means of Fig. 26 to be

$$N_2 = -31{,}300 \text{ lb.}$$

and the maximum tensile stress is

$$s = -\frac{31{,}300}{40.3} + \frac{308{,}000}{50.3} = +5{,}340 \text{ lb./in.}^2$$

CHAPTER VIII

LININGS FOR SHIELD DRIVEN TUNNELS

A. INTRODUCTION

1. Requirements of Lining.—A lining for a shield driven tunnel must be able to withstand the forces to which it may be subjected, which are, (*a*) the weight of the lining; (*b*) the earth pressures and (*c*) the thrust of the shield jacks; it must be permanent, or in other words, it should outlast the use of the structure. It is also usually required that it shall be watertight. Further, as the work of tunneling is laborious, dangerous and expensive, the lining should be brought into the tunnel ready for erection in as finished a state as possible. The actual work of erection in the tunnel should be a simple operation, quickly performed.

2. Primary Lining.—While frequently the complete lining is placed at the time of initial erection, it is sometimes the case that at the time the tunnel is driven it is provided with a primary lining, subsequently supplemented with a secondary inner lining. The purpose of the primary lining is to furnish an immediate support of the ground. This lining must be able to satisfy the requirements as to strength, ease of erection and reasonable watertightness, but does not need to be permanent without further preparation. A metal or a wood lining answers these requirements.

3. Secondary Lining.—If it is thought that the permanence of the primary lining is not assured, an inner lining, usually of concrete, is provided. The function of this lining is either to form the permanent lining or to protect the primary lining so that this will remain permanent. In some cases the secondary lining is provided to give a smooth and pleasing interior finish.

4. Lining Materials.—The lining may be made of almost any of the usual materials of construction. Cast iron has most frequently been used but wood, steel and concrete are also used as lining materials. A description of linings of various materials will be given in the following pages.

FIG. 27.—Cast iron tunnel lining in place. (Courtesy of *New York Transit Commission.*) (Photo by *P. P. Pullis.*)

B. CAST IRON LINING

5. General Description.—In its usual form cast iron lining is a cylindrical structure with a circular cross-section built up of a series of rings, and each ring is made of a number of sections.

Figure 27 shows a cast iron lining erected. Each segment has a web or skin conforming to the curvature of the tunnel and provided with flanges along its four edges. When erected the skin forms an enveloping cylinder which is stiffened by the circumferential flanges. The segments and rings are connected by means of bolts through the flanges.

FIG. 28.—One segment of a cast iron lining.

6. General Details (Fig. 28).—In British linings the skin has a uniform thickness from flange to flange while in American linings the thickness is often increased toward the flanges. For casting reasons the circumferential flanges are tapered and the end flanges, which are commonly called the cross or horizontal flanges, are usually of identical cross-section. To secure full bearing for the bolt heads and nuts on the tapered flanges the bolt holes are bossed. To provide means for waterproofing the joints the flanges are recessed along their inner edges so as to form, when erected, a groove between adjacent segments which may be filled with a waterproofing material. Exceptions to this arrangement will be mentioned later. Triangular bracings or feathers are frequently used to stiffen the flanges against the skin. All intersecting surfaces are filleted. For grouting purposes a tapped and plugged hole is generally provided in the skin of each segment.

7. Patterns of Segments.—The cross joints are radial except, on account of erection conditions, at the "key" or last segment

erected. When a ring of cast iron lining is being erected within the shield in the tunnel there is no space available in front of the ring. The erection space, therefore, is limited to the length of the ring proper and the segments must be moved radially into place. This condition necessitates that the space left for the insertion of the key must be at least as wide at the inside as at the outside of the lining, but for greater convenience of erection it is made wider at the inside. The cross flanges of the key, therefore, taper slightly toward each other at the outside. The two segments adjacent to the key must have one cross flange conforming to that of the key, while the other flange is radial. Three patterns of segments are needed, therefore, for a ring of cast iron lining, namely first, the key segment; second, the two segments adjacent to the key; and third, the remaining segments.

8. Marking of Patterns.—To avoid confusing the segments having only one radial flange with those having two, it is advisable to make the length of the two patterns so different as to be readily distinguishable. This is often done by making the two segments adjacent to the key shorter than the others, the difference in length being equal to the distance between two bolt holes in the circumferential flange. In addition each pattern should have a distinguishing mark, usually a letter, cast in the segment. A similar mark should be cast also in the segment adjacent to the key at the end adjoining the key.

9. Short Rings.—The standard type of ring is used throughout the tunnel except in special cases. When a stretch of ground is met, where the excavation can be carried out only in short lengths at a time ahead of the shield, the work is usually slow. In order to carry it out safely and without undue loss of compressed air it is often advisable under these circumstances to provide rings which are of less width than the standard rings. When going under heavy concentrated loads or under bulkheads of waterways or when the tunnel passes from rock to soft ground it is often feared that the standard lining will not be of sufficient strength, and in those cases short rings are also frequently used, because the increased number of circumferential flanges produces greater strength. In some cases rings of steel castings of the standard patterns are employed for the same purpose.

10. Taper Rings.—For going round curves, either horizontal or vertical, or to correct deviations from the designed line or grade, tapered rings are used with the planes forming a slight

angle, so that the width of the ring varies from point to point. For long radius curves and to correct deviations the difference between the longest and the shortest width may not exceed 1 in. In that case the standard patterns are used for making the castings, with the flanges thickened to produce the proper width of the ring. For sharper radius curves or if greater taper is wanted, special patterns must be made. Three types of tapered rings are needed, one for horizontal deviation, one for vertical depression and one for vertical elevation. In each taper ring every segment is special and must be match marked.

11. Width of Ring.—The width of the rings of the cast iron lining varies in different existing tunnels from 18 to 30 in. The larger ring width has been used for tunnels with diameters of 23 ft. or more, although some large tunnels have been built with smaller ring widths. As the lining is erected within the cover of the tail of the shield, the length in which the tail can be made sets a limit to the possible width of the ring. The length of the tail is limited by the difficulty of steering the shield when the ratio of the length to the diameter of the shield becomes too large. For equal flange depth, skin thickness and strength it makes no material difference in the weight of the lining whether the width of the ring is large or small, because the thickness of the circumferential flange must vary in thickness in proportion to the width of the ring. There is, however, when a large ring-width is used, a material saving in the number of bolts, in the length of joint to be waterproofed, in the work of erection and, most important of all, perhaps, in the reduction of the joint length, every foot of which is a potential source of leakage. It is usually advisable, therefore, to make the rings as wide as the conditions will permit, whatever the diameter of the tunnel may be. It is possible then, that the thickness of the flange may become too great in proportion to the thickness of the skin, leading to casting difficulties. In that case it is worth considering a lining having one or more circumferential ribs in addition to the flanges. Linings of this cross-section are commonly used for shafts and have also been used for tunnels.

12. Example.—As an example the lining for a tunnel of the size of the Rotherhithe tunnel (E-17) may be considered. First a study should be made as to whether a wider ring than that used, which was 30 in., would be possible. The length of the shield for this tunnel was 18 ft. and the ratio of the length to the

diameter was 0.59, while this ratio for the Blackwall tunnel (E-7) shield was 0.71 and for Pennsylvania Railroad East River tunnel (A-19) shield was 0.77. If the shield for the assumed tunnel were made of a length proportional to that of the Blackwall tunnel shield the length would be 21 ft. 9 in. or 3 ft. 9 in. longer than that of the Rotherhithe tunnel. The ring, therefore, could be made 12 in. wider than that of the Rother-

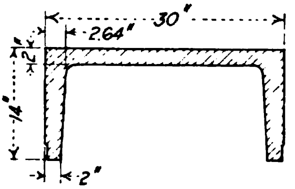

FIG. 29.—Rotherhithe Tunnel (E-17) cross section of cast iron.

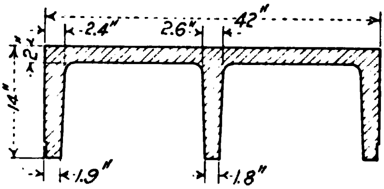

FIG. 30.—Suggested modification for longer ring.

hithe tunnel, or 42 in. wide. Figure 29 shows the cross-section of the lining of the Rotherhithe tunnel. Using the same dimensions as for this lining except increasing the thickness of the

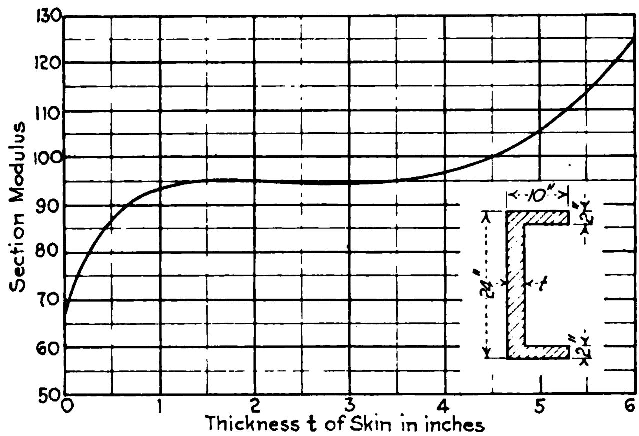

FIG. 31.—Relationship between thickness of skin and section modulus of lining illustrated.

circumferential flanges in proportion to the width of the ring, the thickness of the flange at the skin would be 3.7 in. This flange thickness would be too large in proportion to the thickness of the skin, but by adding a central rib as shown in Fig. 30 the thickness could be reduced to proper proportions.

13. Length of Segments.—In tunnels with a diameter up to about 13 ft. the erection of the lining is generally done by hand. In that case the size of the segment is limited by its weight. In erecting the segment by hand the largest number of men that can get room to lift would usually be four, which would limit the weight to about 350 lb. The greatest overall length of a segment which can be handled conveniently in the tunnel is about equal to the radius of the tunnel. There are, however, some small diameter tunnels which have only three or four segments in a ring in addition to the key. Usually, except in small tunnels, the length of the segment is less than the radius and rarely exceeds 6 or 7 ft., because longer segments are more difficult to cast and because the segments are so stiff that unlike steel structures they cannot be deflected by drifting or other means during erection to procure matching of bolt holes. The necessary flexibility is obtained only in the cross joints and in making the bolt holes in the circumferential flanges large.

14. Length of Key.—The length of the key, measured on the pitch circle of the circumferential bolt holes, is generally equal to the bolt pitch in order to make it possible to stagger the cross joints. Under any circumstances the key should be long enough to permit the last segment erected, before the key is placed, to be swung into position by pivoting on its lower horizontal flange.

15. Thickness of Skin.—The thickness of the skin is determined by the stresses parallel to the longitudinal axis of the tunnel, produced by the pressures of the earth and by the thrust of the shield jacks. The earth pressures produce a bending stress and the shield jacks a compressive stress. The thickness of the skin, therefore, must be so that the tensile stresses from the bending alone and the compressive stresses from the combined forces are both within safe limits. The thrust from the shield jacks may be assumed to be distributed uniformly over the circumference of the skin. If R represents the thrust in pounds per linear inch of circumference and t the thickness of the skin in inches, then the stress due to the shield jacks is R/t lb. per square inch. As regards the earth pressures, if l represents the unsupported length of the skin between the circumferential flanges in inches and p the earth pressure in pounds per square inch, then the maximum moment in inch-pound may be taken to be $pl^2/12$. For linings where the skin is increased in thickness toward the flanges l may be taken as approximately equal to the distance between the centers of gravity of the added triangular

pieces. If the safe compressive stress is 14,000 lb. per square inch and the safe tensile stress 5,000 lb. per square inch, then the minimum skin thickness is determined by

$$R/t + pl^2/2t^2 = 14{,}000 \qquad (21)$$

or

$$pl^2/2t^2 = 5{,}000 \qquad (22)$$

The equation giving the larger value should be used.

16. Economical Thickness of Skin.—An increase of the skin thickness beyond that which is required to transmit the earth pressures to the flanges and to support the thrust of the shield jacks is not economical, because within the limits of practical use it adds to the weight without adding materially to the strength. As an example the variation of the section modulus of a lining with a cross-section as shown is given in Fig. 31. The width of the segment is 24 in., the overall flange depth 10 in. and the flange thickness 2 in. The curve of the section modulus in relation to the skin thickness is plotted for values of skin thickness varying from 0 to 6 in. It will be seen that there is practically no change in the section modulus when t is increased from 1 inch to 3.6 in., although the area of the cross-section is increased from 40 sq. in. to 112 sq. in., in fact, the section modulus is less when the thickness is 3.2 in. than when it is 1.6 in. The practical limits for t are in this case 1 in. and 2 in., between which the area is increased 33 per cent without any material change in the section modulus.

17. Corrosion of Skin.—Although we do not know of any cases in which the skin of a cast iron lining has corroded, it is proper to consider this contingency. It should be remembered, however, that the possible corrosion is independent of the size of the tunnel, so that there is no occasion to increase the skin thickness on account of possible corrosion any more in a large than in a small tunnel built through the same material. If the tunnel is provided with an inner concrete lining there will be no permanent stresses in the skin parallel to the longitudinal axis of the tunnel that cannot equally well be carried by the concrete, and the full thickness of the skin may be subjected to corrosion without affecting the safety of the tunnel as far as the axial stresses are concerned. As regards the circumferential stresses, the concrete lining and the cast iron flanges are usually sufficient to carry these stresses.

18. Depth of Flange.—The tunnel lining is circumferentially subjected to a thrust N and a moment M by the external forces. The determination of the values of M and N are shown in Chap. VII. If A is the area of the cross-section of the lining per linear foot of tunnel in square inches and S the corresponding section modulus in inches cubed, then the stress s in pounds per square inch is expressed by

$$s = N/A \pm M/S \tag{23}$$

For a given section modulus the area of the cross-section decreases as the flange depth is increased. Consequently less cast iron is used when the flanges are made deep. On the other hand, more excavation has to be made with deeper flanges and, if an internal lining is to be used, more concrete is needed. The economical depth is best determined by comparative estimates of cost.

19. Flange Depth of Existing Tunnels.—As might be expected the flange depths of existing tunnel lining do not follow any well defined law, but roughly speaking, if f represents the overall flange depth in inches and D the external diameter in feet, then for tunnels in London clay

$$f = 0.4D \tag{24}$$

and for tunnels in waterbearing ground

$$f = 0.5D \tag{25}$$

represent approximately the relation between flange depth and diameter. These equations may be used for initial selection of flange depth.

20. Stiffness of Circumferential Flanges.—For proper stiffness the proportion between the free depth of the flange, measured from the inside of the skin to the inner edge of the flange, and the thickness of the flange, measured at the skin, should not exceed a certain limit. Judging from the proportions used in existing linings this limit may be taken as 5.

21. Taper of Flange.—The useful flange area, as far as the section modulus is concerned, is that near the inner edge of the flange. Consequently the taper of the flange should be made as small as the casting of the segment will permit. While this to some extent depends on the individual foundry, a taper of ⅜ in. in 12 in. may be taken as an average minimum.

22. Machined Joints.—In order to obtain a structure of proper shape and alignment, subject to the minimum chance of leakage and involving the least work of erection, all the flanges should

have the contact surfaces machined. The machining adds to the cost of fabricating the lining, but where the facilities are present for machining this cost is amply repaid in the lower erection cost and in the better structure obtained.

23. Unmachined Joints.—In the earlier days of cast iron tunnel linings unmachined joints were common practice. The tunnels were small and usually built through dry ground. The castings were made with a beading along the outside circumferential flange on line with the skin so as to insure that the thrust from the shield jacks would be transmitted through the skin. By this arrangement a deep groove was formed between adjacent rings, which was used for waterproofing the joints. While this method places the waterproofing at the proper position, namely at the point of entrance of the water, it makes the alignment of the ring and the individual segments uncertain. The rough castings have no exact or uniform ring width and the bolts cannot be tightened to a definite bearing. The segments have been made also without the beading and a thin strip of wood placed between the rings. This is equally unsatisfactory, because the thrust of the shield jacks produces unequal compression of the wood. The cross joints are made in either case with similar wood packings. The shape of the tunnel is difficult to maintain with such cross joints.

24. Calking Grooves.—To secure water tightness of the machined joints a calking groove is provided around the inner edge of the flanges by setting back the casting from 1/8 to 1/4 in. from the face for a depth of from 1 to 2 in. When the two flanges of adjacent segments or rings are placed together there is then formed a narrow groove which is filled with the waterproofing material.

25. Machining of Calking Grooves.—Owing to the small width of the calking groove it is difficult in casting the segments to obtain uniformly a groove of the proper width. The result is that on some of the segments the subsequent machining of the flange removes the groove almost entirely, making the calking operation in the tunnel laborious and expensive. This can be remedied only to a certain extent by rigid inspection of the castings, requiring chipping where the groove is not wide enough. It is possible that in spite of the additional cost of manufacture it would pay to have the calking groove machined, because it would lessen the cost of calking, which is done in the tunnel by

high priced tunnel labor and often under compressed air where the wages are still higher.

26. Bolts.—The connection of the segments and rings is made by means of bolts. The bolts have a standard thread and hexagonal nuts and heads. Washers of sufficient thickness should be placed under the heads and nuts. The bolt thread may be cut or pressed. An upset thread is not advisable, because for the same thread diameter the shank is smaller producing greater elongation of the bolt and greater deformation of the lining.

27. Bolt Stress in Cross Joint.—The stress in the bolts in the cross joints may be determined by taking the moments around the edge about which the segment tends to turn, or perhaps better, around a point 1 in. inside of the edge. Let (Fig. 32) B represent the bolt stress in pounds, M the moment in inch-pounds, N the thrust in pounds, n the distance from the neutral axis to the outside edge in inches, b the distance from the centerline of the bolts to the outside edge in inches and f the effective depth (depth of flange less the depth of the calking groove) of the flange in inches, then if the segment tends to turn around the outside edge

$$B = \frac{M - (n - 1)N}{b - 1} \tag{26}$$

If the segment tends to turn around the inside edge, then the bolt stress is

$$B = \frac{M - (f - n - 1)N}{f - b - 1} \tag{27}$$

The required bolt area per linear foot of tunnel is found by dividing the bolt stress B by the permissible unit stress in the bolt.

28. Location of Bolts in Cross Joints.—The bolts in the cross joints should be placed so that they will actually perform the duty for which they are intended. This is perhaps the most difficult part of the design of a cast iron lining. Consider for example a cross flange as shown in Fig. 33. The computations may have shown that three bolts of a given diameter are necessary. If the bolts are placed as shown and the tendency of the joint is to open at the outside, it cannot be expected that the center bolt will carry its proportional load, with the result that the two outside bolts will receive a greater stress than calculated. If the bolts are arranged as shown in Fig. 34, it is probable that

when the segment tends to turn around the outside edge the two end bolts in the inner row will carry practically all the stress, and when the tendency is to turn around the inner edge, the two bolts in the outer row will carry the greater part of the stress. The best arrangement would be to use few bolts of large diameter and arranged in such a manner that the stress in them can be calculated (Fig. 35).

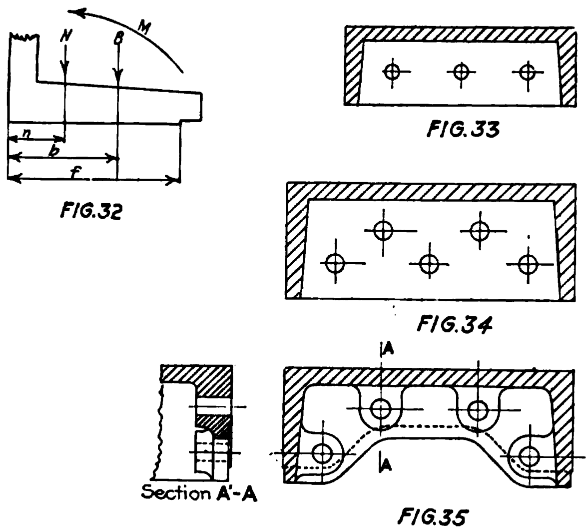

FIG. 32.—Diagram of radial or "cross" joint.
FIG. 33.—Plan of a cross joint.
FIG. 34.—Plan of a cross joint.
FIG. 35.—Suggested arrangement of bolt holes in cross joint.

29. Unit Stress in Bolts.—The elongation of the bolts under the stress produces an opening of the joint and consequently deformation of the lining. In order to keep these as small as possible the maximum stress in the bolt should be kept low. The use of steel with high elastic limit for the bolts does not decrease the elongation, because the modulus of elasticity is about the same for all grades of steel.

30. Staggering of Cross Joints.—While the first cast iron lined tunnels were built with continuous cross joints it is now common practice to stagger or break the joints. When this is done the circumferential flanges act as splices for the cross joints and assist the bolts in these joints. The additional stiffness of the lining gained thereby is very marked, and a cast iron lining should be designed always so that it can be built with staggered cross joints.

31. Bolts in the Circumferential Flanges.—The bolts in the circumferential flanges serve to keep the rings together. When the cross joints are staggered, the friction they produce between the flanges also assist the bolts in the cross joints, but this friction should not be taken into account in the designing, because experience shows that the thrust of the shield jacks produces a loosening of the bolts some distance back of the shield. No definite rules can be given as to the size of these bolts, because the work they perform is indefinite. If local settlements occur in the tunnel the bolts will be stressed, but it is uncertain to what extent. During the construction of the Pennsylvania Railroad tunnels under the Hudson River (A-18) heavy local settlements were produced at experimental points, but they did not seem to affect the bolts in the circumferential flanges. The best rule is to make the bolts capable of carrying a load as great as that the circumferential flanges can carry. To make them stronger is useless. For practical reasons it is well to have these bolts of the same size as those in the cross flanges, unless the length of the bolts is different.

32. Staggering of Bolts in Circumferential Flanges.—In some cases the bolts in the circumferential flanges have been placed in two pitch circles so as to distribute the bolts better over the flange width. Unless absolutely necessary for proper connection, this arrangement should not be used, because it has the tendency of reducing the section modulus of the cross-section to a marked degree by bringing the bolt hole close to the inner edge of the flange.

33. Strength of Cross Flanges.—The cross flanges are usually made of the same cross-section as the circumferential flanges. It should, however, be investigated whether they are strong enough to carry the stress of the bolts. Sufficient strength may be obtained by raising the bosses around the bolt holes as shown in Fig. 35. The thickness and width of the boss should be such that the shear and the bending stress at the junction with the circumferential flange is within safe limits.

34. Bolt Holes.—The bolt holes are usually cored. They are generally about one-quarter of an inch larger in diameter than the bolts in order to facilitate erection. In principle this is unsatisfactory, because it permits distortion of the lining and increases the tendency to leak, but it is necessary on account of the rigidity of the cast iron.

35. Grout Holes.—For grouting purposes a hole about 1½ in. in diameter is usually provided in the skin of each segment. The hole is tapped, either with a pipe or bolt thread. The former makes it easier to secure a watertight plug.

36. Waterproofing.—Unless watertight a tunnel will perform the function of a drain for the surrounding soil. If the ground contains percolating water only it may be sufficient to make the resistance to flow greater through the lining than through the ground to prevent infiltration. When the water in the ground is present under a head the lining must be watertight to prevent leakage into the tunnel. A tunnel is rarely, if ever, absolutely watertight. Provisions must be made, therefore, for collecting the seepage water in sumps whence it can be removed by pumping.

37. Waterproofing Unmachined Joints.—In small tunnels built through ground with percolating water only and in which the flanges are not machined the wood packing in the cross joints forms a resistant to percolation which is generally sufficient. Usually the wood packing is narrower than the flange, leaving a groove at the inside of the flange which is pointed with neat cement, adding to the resistance to percolation. The groove between the adjacent circumferential flanges which, as described, extends nearly to the back of the lining, is usually provided with a soft packing at the bottom and then filled with neat cement. The common experience with waterproofing of this kind is that if a leak occurs it may be stopped, but will break out somewhere in the vicinity. In that case the best procedure is to let the water enter, collect it in a pipe at the point of entry and carry it through the pipe to the ivnert.

38. Waterproofing under a Head of Water.—When the water is present under a head the flanges of the cast iron lining are usually machined and provided with a calking groove at the inside edge. The waterproofing is done by means of calking with a rust cement or with lead.

39. Rust Calking.—The principle of rust calking is to introduce into the groove finely divided and tightly packed steel or iron mixed with some compound that will produce a rapid and thorough rusting of the metal. Usually iron or steel borings or filings mixed with sal ammoniac form the calking mixture. Sometimes sulphur is added to produce a more rapid hardening. The proportions in which the materials are mixed and the method of

application are more fully described in Chap. XIII. By rusting, the particles of metal are formed into a solid mass of increased volume which in itself is watertight and which presses tightly against the sides and the bottom of the groove. As the groove is coated no rusting together of the calking material and the cast iron of the lining is obtained. It is probable that if the groove were uncoated the calking would be improved as it would have a better bond. The coating is the pitch described on p. 111.

40. Lead Calking.—Lead calking is generally applied in the form of a heavy wire placed in the groove and calked tight. The calking groove is usually made narrower than when rust calking is used, because equally efficient results can be obtained with a narrow groove. In the subaqueous tunnels of the rapid transit system of New York City the calking groove is one-quarter of an inch wide and the lead wire used was oval in cross-section, the largest diameter being one-half inch and the smallest one-quarter inch. No doubt lead-wool might be used.

41. Methods Compared.—There seems to be no difference in the efficacy of the two kinds of calking methods. Rust calking cannot be applied against a head of water and must be done, therefore, under air pressure. Lead calking requires a more expensive material, but usually can be done in normal air.

42. Waterproofing Bolt Holes.—As the bolts of the cast iron lining are located outside of the calking zone they must be waterproofed individually. The usual method is to place a grummet of hemp, dipped in red lead and oil, under the washers at the heads and nuts of the bolts. In some cases, where the shank of the bolts was smaller than the thread, a wrapping of hemp, dipped in red lead and oil, has been used and in other cases lead washers, consisting of short lengths of lead pipe, or specially cast, have been placed under the washers of the bolts. When the bolts were tightened the lead washers were forced down into a shallow conical groove in the bolt holes. The efficacy of this method depends on the washers being just the right length. An attempt has been made to bring the bolts within the calking zone by carrying the calking groove around the bolts. The difficulty in calking behind the bolts is, however, so great as to make this method generally too expensive, and the results have not shown any improvement over the simple calking groove.

43. Weight of Cast Iron Lining.—The weight of cast iron lining depends on the design and, therefore does not follow any definite

law. Figure 36 shows the weight per linear foot of tunnel in pounds in relation to the external diameter of various tunnels in London Clay and also a curve having the equation

$$W = 14D^2 \tag{28}$$

where W is the weight of the lining in pounds per linear foot of tunnel and D the external diameter in feet. This curve approximately

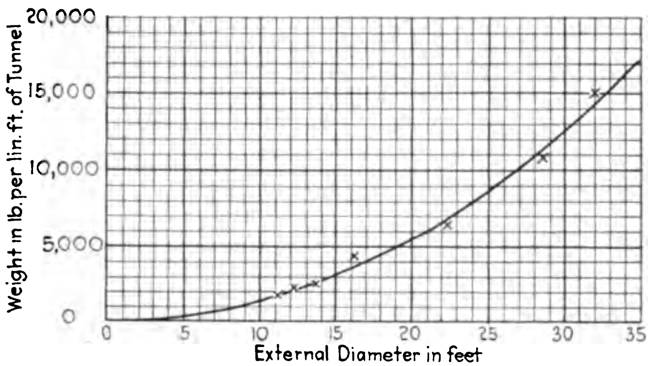

Fig. 36.—Cast iron lined tunnels in London clay. Relationship between diameter and weight of cast iron.

satisfies the actual weights. Figure 37 shows a similar curve for tunnels in firm waterbearing ground, having the equation

$$W = 19D^2 \tag{29}$$

and also the actual weights of various tunnels in waterbearing

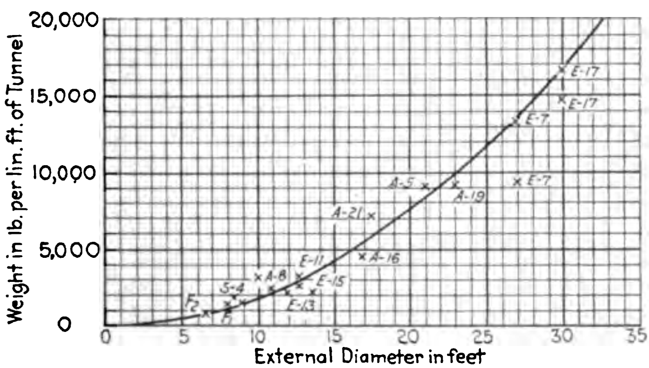

Fig. 37.—Cast iron lined tunnels in water bearing ground. Relationship between diameter and weight of cast iron.

ground. Figure 38 shows the same relation of tunnels in Hudson River silt and a curve having the equation

$$W = 22D^2 \tag{30}$$

These curves should be used only for establishing a provisional value of W and they should not be used for tunnels larger than 30 ft. in diameter without further investigation.

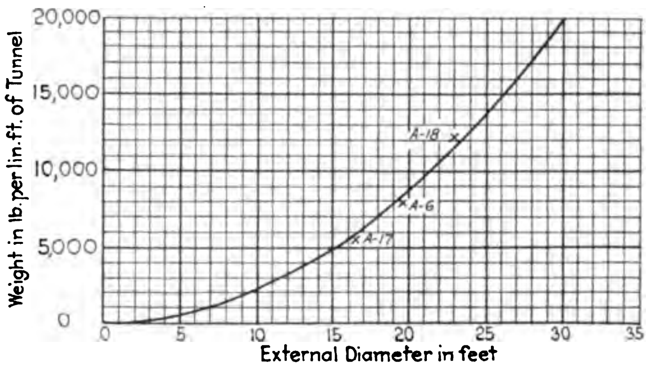

FIG. 38.—Cast iron lined tunnels in Hudson River silt. Relationship between diameter and weight of cast iron.

44. Specifications for Cast Iron Tunnel Lining.—In the following the specifications for cast iron lining used for rapid transit tunnels in New York City are quoted:

"Cast iron shall be tough gray iron made by the cupola process and shall contain not more than six-tenths (0.6) per centum of phosphorus and not more than twelve one-hundredths (0.12) per centum of sulphur. No mill cinder iron, white or burnt iron or inferior scrap will be permitted in the composition.

"The quality of iron entering into the castings shall be determined by means of the 'Arbitration Bar.' This is a bar one and one quarter (1¼) in. in diameter and 15 in. long, cast under the same circumstances as those which attended the casting of the full size piece. This bar shall sustain at the center when resting on two dull knife edges 12 in. apart, a load of 3,000 lb. with a deflection of at least one-tenth of an inch before rupture. Two sets of two bars shall be cast from each heat; one set from the first and the other set from the last iron entering into castings. Each set of two bars shall be made in a single mold.

"Castings shall be made with a high sinking head so as to insure sound metal throughout. They must have clean, smooth surfaces and must be free from blow holes, cold shuts, flaws, fins and surface imperfections. Castings having blow holes plugged or puttied will be rejected. Castings shall conform accurately to the form and dimensions shown on the drawings and sufficient allowance must be made for planing. Each casting shall have its distinguishing letter or number cast on at the place

indicated on the drawings. All castings shall be neatly chiseled and wire-brush dressed before leaving the foundry.

"Bolt holes in the segments of the cast iron tunnel lining may be either cored or drilled. They shall be circular, of $\frac{1}{4}$ in. larger diameter than the diameter of the bolt used, shall be correctly spaced and shall be perpendicular to the plane of the joint. They shall be filleted on the face opposite the joint as shown on the drawings.

"After being cleaned and while still hot, at a temperature of about 300 deg. F., . . . castings . . . shall be dipped in a bath of coal-tar pitch. The pitch shall be destilled free from naptha, shall be deodorized with a mixture of 5 per centum of linseed oil and must not be hard and brittle when cold. The pitch must be heated carefully in a suitable vessel to a temperature of 300 deg. F. and must be maintained at this temperature during the process of dipping. The pitch must be replenished and replaced frequently as it deteriorates or thickens. If in any case it should be impracticable to dip the castings in pitch before cooling, they shall be completely coated, inside and outside, immediately after cleaning, with linseed oil to prevent rusting until dipped. When dipped, the castings shall remain in the pitch bath until they have attained a temperature of 300 deg. F. No casting shall be dipped after rust has set in. After being dipped, the castings shall be removed slowly from the bath and laid on skids to drip and cool before being machined.

"All joints of tunnel segments shall be planed to correct form and dimensions. After a segment has been planed, it shall be tested by applying substantial steel templates to all planed faces, the templates having the exact form required for the faces and having plugs attached of the exact diameter of the bolts outside the threads and of sufficient length to pass entirely through the cored holes. The plugs must enter the bolt holes freely and the joints must correspond exactly with the template. The templates shall be furnished by the contractor and shall be satisfactory to the engineer.

"Taper rings for tunnel lining shall have their longitudinal joints planed first and shall then be planed on the circumferential joints while the segments, forming a complete ring are firmly bolted together. The segments of each taper ring shall be distinctively marked so that they may be reassembled readily in proper order and shall be shipped together.

"Each tunnel segment shall have a rebate extending along the edge of the flange to form a calking recess after the segments are erected. The rebate shall be formed in molding, shall be $1\frac{1}{4}$ in. wide, and may vary in depth, from the machined face of the flange, between $\frac{1}{16}$ and $\frac{3}{16}$ in.

"In each type of tunnel ring, except taper rings, all similar segments shall be of such uniformity in dimensions that they will be interchangeable with each other and with similar segments of other rings of the same type. The spacing of bolt holes must be so accurate that any two

rings can be bolted together in any relative position. These requirements shall be tested whenever required by the Engineer by assembling and bolting up the segments for at least 3 rings in a horizontal position, under which conditions the faces of the rings thus bolted up shall be true plane surfaces. The outer edge of any ring shall vary nowhere more than ½ in. from that shown on the drawings.

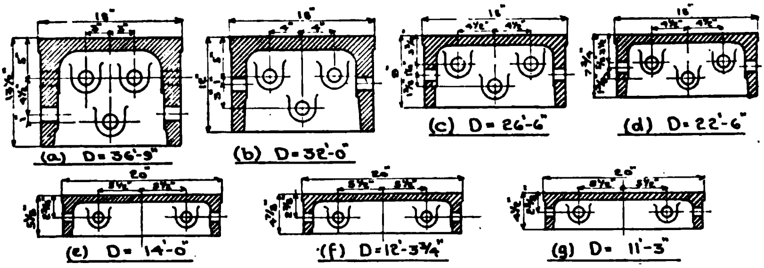

FIG. 39.—Cast iron linings in London clay, cross sections.

"Each tunnel segment shall be tapped with a hole near the center for grouting connection. The hole shall be threaded with a standard bolt thread and closed by a screw plug.

"Planed surfaces shall be coated before leaving the shop with a mixture of white lead and tallow.

"The actual finished weight of any casting . . . shall not differ more than 2½ per centum from the Engineer's calculated weight. In calculating weights, the weight of 1 cu. ft. will be taken at 450 lb."

45. Characteristics of Existing Cast Iron Linings in London Clay.—As previously stated the dimensions of cast iron linings have been determined largely by judgment and by comparison with those already built. This has caused some divergence in the proportioning according to the judgment of the designer. The greatest uniformity is found in the tunnels built through London Clay. Figure 39 shows the cross-section of linings built through this material and having external diameters varying from 11 ft. 3 in. to 36 ft. 9 in. The dimensions of these linings are tabulated in Table VI. In order to obtain a better comparison the flange depth, the flange thickness, and the section modulus are shown in Fig. 40 in relation to the external diameter. It should be noted that the flange thickness and the section modulus, in order to compare them on a uniform basis, are plotted per linear foot of tunnel.

46. Characteristics of Existing Tunnels in Waterbearing Ground.—The cross-sections of cast iron lined tunnels built

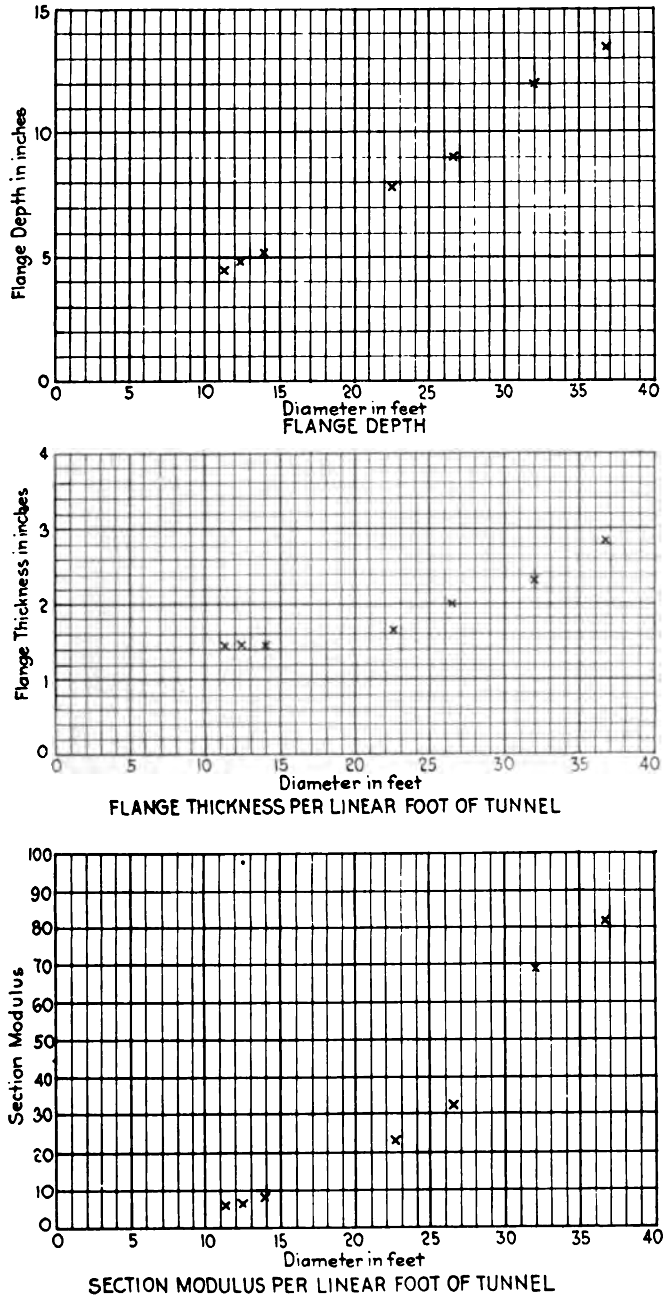

Fig. 40.—Cast iron linings in London clay. Relationship between diameter of tunnel and flange depth, flange thickness per linear foot of tunnel and section modulus per linear foot of tunnel.

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through waterbearing ground are shown in Fig. 41, and their dimensions in Table VII. Figure 42 shows the flange depth, flange thickness, and section modulus plotted in relation to the external diameter. For proper comparison the bolt diameter plotted is the outside diameter of the thread.

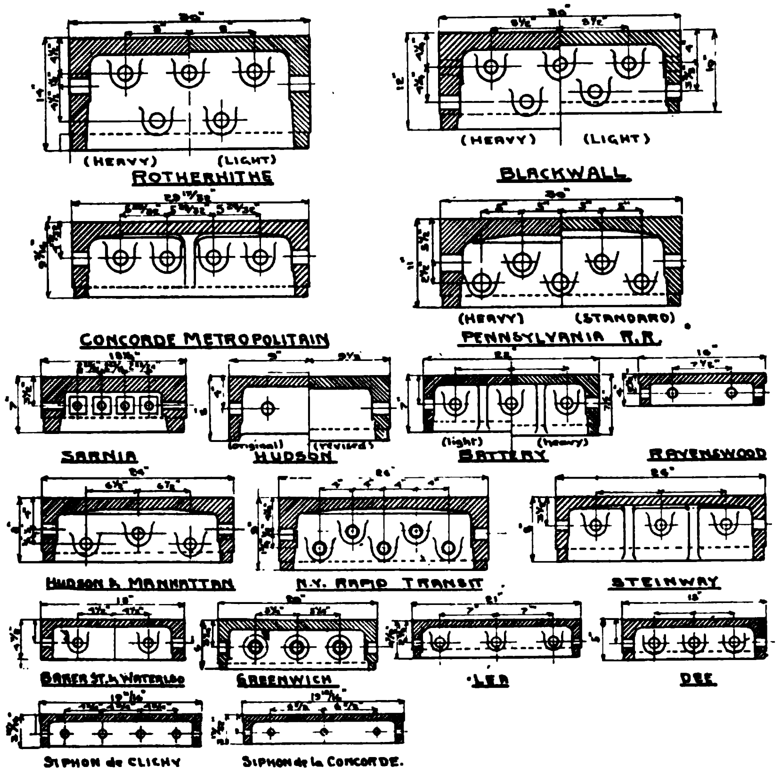


FIG. 41.—Cast iron linings in waterbearing ground—cross sections.

47. Example.—Design of a cast iron lining for a tunnel with a clear inside diameter, *d*, of 18 ft. to be driven through soft ground. Above the top of the tunnel is 30 ft. of water and 15 ft. of earth weighing 100 lb. per cubic foot. The shield will permit a ring 30 in. wide to be used and the thrust of the shield jacks is 12,000 lb. per square foot of tunnel area. The safe tensile stress is 5,000 lb. per square inch and the safe compressive stress is 14,000 lb. per square inch. The air pressure is 15 lb. per square inch.

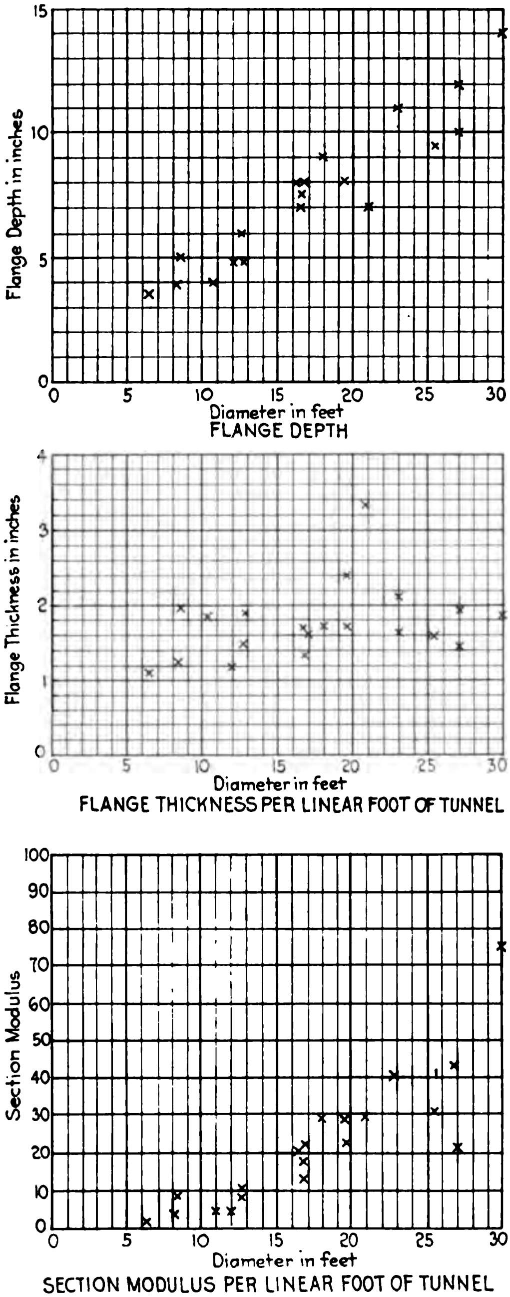


Fig. 42.—Cast iron linings in waterbearing ground. Relationship between diameter of tunnel and flange depth, flange thickness per linear foot of tunnel and section modulus per linear foot of tunnel.

TABLE VI.—CAST IRON LININGS IN LONDON CLAY

Ext. dia., feet	Depth of flange, in.	Width of ring, in.	Flange thickness, in.		Skin thickness, in.	No. of segments	Dia. of bolt, in.	Dia. bolt hole, in.	No. bolts in flanges		Section modulus per linear foot
			At skin	At edge					Cross	Circ.	
36.75	13.50	18	2.50	1.75	1.50	19	1½	1¾	3	72	82.0
32.00	12.00	18	2.00	1.50	1.50	17	1¼	1½	3	113	69.0
26.50	9.00	18	1.62	1.37	1.25	15	1¼	1½	3	97	32.6
22.50	7.75	18	1.50	1.25	1.12	13	1⅛	1⅜	3	83	23.4
14.00	5.12	20	1.25	1.12	0.87	8	1	1¼	2	57	8.0
12.31	4.87	20	1.25	1.12	0.87	7	⅞	1⅛	2	47	6.7
11.25	4.50	20	1.25	1.12	0.87	7	⅞	1⅛	2	41	6.0

(*a*) *External Diameter.*—Allow 6 in. for deviations during the driving. From Equation (25) the external diameter may then provisionally be determined by

$$D = 18.00 + 0.50 + 2 \times 0.5D/12$$

or

$$D = 20.18 \text{ ft.}$$

(*b*) *Weight of Lining.*—(See par. **43.**)

$$W = 22D^2 = 9{,}000 \text{ lb.}$$

(*c*) *Moments.*—(See Chap. VII, par **31.**)

Assume $d = D - 0.48 = 19.7$ ft. From Fig. 25, the values of m_1 and m_2 are found at axis level

$$m_1 = 0.31$$
$$m_2 = -0.33$$

and at bottom

$$m_1 = -0.37$$
$$m_2 = 0.34$$

The moments at axis level and bottom are then

$$M_2 = 19.7(0.31 \times 100 \times 20.18^2 - 0.33 \times 9{,}000) = 190{,}000 \text{ in.-lb.}$$

$$M_3 = 19.7(-0.37 \times 100 \times 20.18^2 + 0.34 \times 9{,}000) = -237{,}000 \text{ in.-lb.}$$

(*d*) *Thrusts.*—(See Chap. 7, par. **32.**)

From Fig. 26 the value of the constants n_1 and n_2 are found at axis level

$$n_1 = -0.05$$
$$n_2 = -0.25$$

and at bottom

$$n_1 = -0.35$$
$$n_2 = -0.01$$

TABLE VII.—CAST IRON LININGS IN WATERBEARING GROUND

Ref. No.	Tunnel	Ext dia., feet	Depth of flange, in.	Width of ring, in.	Flange thickness, in.		Skin thickness, in.		Number of segments including key	Dia. of bolt, in.	Dia. bolt hole, in.	Number of bolts in flanges		Section modulus per linear foot
					At skin	At edge including calking groove	At middle	At flang				Cross	Circ.	
(E-17)	Rotherhithe (under river)	30.00	14	30	2.64	2.00	2.00	2.00	17	$1\frac{1}{2}$	$1\frac{7}{8}$	5	79	75.0
(E-17)	Rotherhithe	30.00	14	30	2.67	2.00	1.75	1.75	17	$1\frac{1}{2}$	$1\frac{7}{8}$	5	79	75.0
(E-7)	Blackwall (under river)	27.00	12	30	2.83	2.00	2.00	2.00	15	$1\frac{1}{2}$	$1\frac{3}{4}$	5	70	43.4
(E-7)	Blackwall	27.00	10	30	2.14	1.50	1.50	1.50	15	$1\frac{1}{2}$	$1\frac{3}{4}$	5	70	21.4
(F-12)	Concorde Metropolitan	25.51	$9\frac{7}{16}$	$29\frac{17}{32}$	2.19	1.75	1.56	1.94	13	$1\frac{3}{8}$	$1\frac{3}{4}$	4	98	30.3
(A-18)	Pennsylvania Railroad Hudson	23.00	11	30	2.86	2.39	2.00	2.88	12	1.62	$2\frac{1}{8}$	5	67	50.3
(A-18)	Pennsylvania Railroad Hudson	23.00	11	30	2.25	1.78	1.50	2.37	12	1.52	$1\frac{7}{8}$	5	67	
(A-19)	Pennsylvania East River	23.00	11	30	2.25	1.50	1.50	2.37	12	1.52	$1\frac{7}{8}$	5	67	
(A-5)	Sarnia	21.00	7	$18\frac{1}{4}$	2.92	2.12	2.00	2.00	14	0.87	1	4	157	29.7
(A-6)	Hudson (First Type)	19.50	8	20	1.62	1.25	1.25	1.25	10	1.25	$1\frac{5}{8}$	3	55	23.1
(A-6)	Hudson (Second Type)	19.44	8	$20\frac{1}{4}$	2.25	1.75	1.50	2.50	12	1.25	$1\frac{7}{16}$	3	67	29.0
(A-27)	Old Slip. Rapid Transit, New York	18.00	9	26	2.00	1.75	1.37	2.00	10	1.16	$1\frac{5}{8}$	5	55	29.9
(A-21)	Steinway	16.83	8	26	1.57	1.37	1.12	1.50	9	1.12	$1\frac{1}{4}$	3	49	22.3
(A-16)	Battery	16.67	7	22	1.37	1.12	1.12	1.12	9	1.00	...	3	49	13.3
(A-16)	Battery	16.71	$7\frac{1}{2}$	22	1.62	1.37	1.12	1.12	9	....	...	3	49	17.8
(A-17)	Hudson & Manhattan	16.58	8	24	1.87	1.50	1.44	2.00	10	1.25	$1\frac{1}{2}$	3	55	20.8
(E-15)	Baker St. & Waterloo	12.83	$4\frac{7}{8}$	18	1.50	1.37	0.87	0.87	7	0.87	$1\frac{1}{8}$	3	53	8.7
(E-11)	Greenwich	12.75	6	20	1.42	1.12	1.25	1.25	9	1.37	$1\frac{5}{8}$	3	47	10.3
(E-13)	Lea	12.16	$4\frac{7}{8}$	21	1.12	1.00	0.87	0.87	7	0.87	...	2	29	5.3
(A-8)	Ravenswood	10.83	4	16	1.25	1.25	1.25	1.25	10	1.00	...	2	51	4.6
(S-4)	Dee Sewer	8.50	5	18	1.50	1.44	1.00	1.00	6	1.00	$1\frac{1}{4}$	3	42	9.3
(F-1)	Siphon de Clichy	8.20	$3\frac{15}{16}$	$19\frac{11}{16}$	1.00	1.00	1.00	1.00	6	1.00	...	4	51	3.9
(F-2)	Siphon de la Concorde	6.54	$3\frac{5}{8}$	$19\frac{11}{16}$	0.91	0.91	0.78	0.78	5	0.79	...	3	21	2.7

The thrusts at axis level and bottom are then

$$N = -0.05 \times 100 \times 20.18^2 - 0.25 \times 9{,}000 - \tfrac{1}{2}(3{,}420 - 2{,}160)20.18 = -17{,}000 \text{ lb.}$$

$$N = -0.35 \times 100 \times 20.18^2 - 0.01 \times 9{,}000 - \tfrac{1}{2}(3{,}420 - 2{,}160)20.18 = -27{,}100 \text{ lb.}$$

(*e*) *Area of Cross-section.*—Judging from the evidence of existing tunnels it is probable, that the gross cross-sectional area will be about 30 sq. in. This value will be used provisionally.

(*f*) *Section Modulus.*—Equation (20), Chap. VII, par. **34**, will now read

$$5{,}000 = -\ 17{,}000/30 + 190{,}000/S$$

(as the maximum tensile stress will occur at axis level, the moment and thrust for this point are used).
From this equation is found

$$S = 34 \text{ in. cubed}$$

(*g*) *Skin Thickness.*—(See Chap. VIII, par. **15**.)

The total thrust of the shield jacks is $12{,}000 \times 320 = 3{,}840{,}000$ lb., and

$$R = 3{,}840{,}000/761 = 5{,}000 \text{ lb. per linear inch}$$

The earth pressure per square inch at axis level is

$$p = 0.44 \times 30 + 0.70 \times 25 = 30.7 \text{ lb./in.}$$

Inserting these values in (21), the thickness t of the skin will be determined by

$$5{,}000/t + 30.7 \times 26^2/2t^2 = 14{,}000$$

or

$$t = 1.06 \text{ in.}$$

Inserting the value of p in (22), the following expression is obtained

$$30.7 \times 26^2/2t^2 = 5{,}000$$

or

$$t = 1.44 \text{ in.}$$

The latter value is the larger and should be used, so that the skin thickness should be made $1\frac{7}{16}$ in.

(*h*) *Cross-section.*—It is now required to proportion the cross-section so that the width of the ring is 30 in., the skin thickness $1\frac{7}{16}$ in. and the section modulus 34 per linear foot. The flange depth may be assumed provisionally to be (see (25) par. **19**) 10 in. The problem then is to select such a flange thickness that

the requirements are satisfied. Try, therefore, a cross-section as shown in Fig. 43.

First the location of the neutral axis is found by taking moments around the inner edge of the flange, and it will be found that its distance from the inner edge is 7.37 in. Next the moment of inertia is determined around this axis and is found to be 250 per linear foot of tunnel. The least section modulus is then $250/7.37 = 34$ per linear foot of tunnel. This section, therefore, satisfies the given conditions.

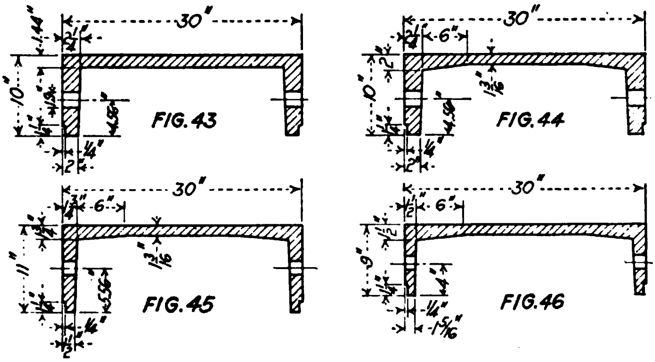


FIG. 43.—Tentative cast iron cross section to meet requirements of example.
FIG. 44.—Second cast iron cross section to meet requirements of example.
FIG. 45.—Third cast iron cross section to meet requirements of example.
FIG. 46.—Cast steel cross section to meet requirements of example.

As the section is shown, however, the thickness of the flange is too great in proportion to the thickness of the skin, and it is necessary to thicken the skin toward the flanges, but by doing this it may be possible to decrease the thickness of the other part of the skin. The effective length of the skin may be assumed to be 21.5 in. (see par. **15**). The skin thickness is then determined by

$$5{,}000/t + 30.7 \times 21.5^2/2t^2 = 14{,}000$$

or by

$$30.7 \times 21.5^2/2t^2 = 5{,}000$$

From the first equation the value of t is 0.91 in. and from the second, $t = 1.19$ or $1\frac{3}{16}$ in., which is the value to use. The cross-section will then be as shown in Fig. 44. The gross area of this cross-section is 78.2 sq. in. or 31.3 sq. in. per linear foot of tunnel.

In order to determine, whether this is the most economical

cross-section another section with a different flange depth should be investigated. Try, for example a cross-section as shown in Fig. 45, with a flange depth of 11 in. It will be found that this cross-section has a section modulus of 33.6 per linear foot and, therefore, may be used. The question of whether this or that section shown in Fig. 44 should be used, is one of economy. The section with the 11 in. flange has a gross cross-section area of 28.4 sq. in. or 2.9 sq. in. per linear foot of tunnel less than that with the 10 in. flange. The saving in cast iron is, therefore, approximately 550 lb. per linear foot of tunnel. On the other hand, there is approximately 0.2 cu. yd. more excavation per linear foot of tunnel. If the cast iron costs \$0.04 per pound in place, and the cost of excavation is \$30.00 per cubic yard, the saving in cast iron is

$$\$0.04 \times 550 = \$22.00$$

and the additional cost of excavation is

$$\$30.00 \times 0.2 = \$6.00$$

There is, therefore, in this case a saving of \$16.00 per linear foot of tunnel in using the 11 in. flange depth instead of 10 in. flange depth.

The proportion between the unsupported flange depth and the flange thickness for the cross-section shown in Fig. 45 is

$$9.25/1.75 = 5.3$$

It is, therefore, not advisable to use a section with still greater flange depth. (See par. **20.**)

(*i*) *Bolts in Cross Joint.*—(See par. **27.**) Locate bolts in two rows, one 3½ in. from the inner edge and the other 4 in. from the outer edge. The maximum stress in the inner row is then

$$B = \frac{190,000 - 1.67 \times 17,000}{6.5} = 25,000 \text{ lb.}$$

and in the outer row

$$B = \frac{237,000 - 6.08 \times 27,100}{4.75} = 15,200 \text{ lb.}$$

If two 1½-in. bolts are used in each row, the maximum stress in the bolts will be

$$25,000/2.588 = 9,700 \text{ lb. per square inch.}$$

C. LININGS OF STEEL CASTINGS

48. Suitability.—While linings of steel castings have been used in special cases for short lengths of tunnel, otherwise lined with cast iron, they have not up to the present time been used as the standard lining material. As, however, the art of making steel castings is being developed, it is possible that the greatest obstacle to their use, namely their cost, may be removed. The material itself has many advantages over cast iron, the most important being that the tensile strength is much greater. A tunnel lining of steel castings may be made, therefore, of a lighter cross-section than when made of cast iron.

49. Welding of Segments.—Steel castings may be welded. It is probable that by welding the joints of the lining the waterproofing of the tunnel may be attained more readily and effectively than by the present methods used in cast iron linings. It is also probable that the welding may be developed to replace partly or wholly the bolts for connecting the segments.

50. Thickness of Skin.—As the tensile strength of steel castings is about the same as the compressive strength, the skin thickness will be determined by the combined compression due to the thrust of the shield jacks and the earth pressures (see par. **15**). If the safe compressive stress is 14,000 lb. per square inch, then the skin thickness t will be determined by

$$R/t + pl^2/2t^2 = 14{,}000 \qquad (31)$$

where R represents the thrust of the shield jacks in pounds per linear inch of circumference, p the earth pressures in pounds per square inch and l the unsupported length of the skin.

51. Example.—Figure 46 shows a lining of steel castings, for a tunnel under the conditions stated in the example, par. **47**. In this case the gross area of the lining of steel castings is about 84 per cent that of the cast iron lining shown in Fig. 45.

D. STRUCTURAL STEEL LINING

52. Structural Steel Used in Existing Tunnels.—In one of the few instances where rolled steel has been used in the United States for lining a shield driven tunnel, the material of which the lining was made was 13-in. ship channels and the steel was used for experimental purposes only. A tunnel on the Frankfurt-Berlin railroad at Elm, Germany (G-10), was lined with a primary

lining of 12-in. channels. This tunnel is notable for being the largest tunnel driven by shield. In both of the cases stated the web of the channels was placed so as to form the skin of the lining, and the flanges of the channels formed internal ribs. Special rolled shapes have been used in several tunnels built in

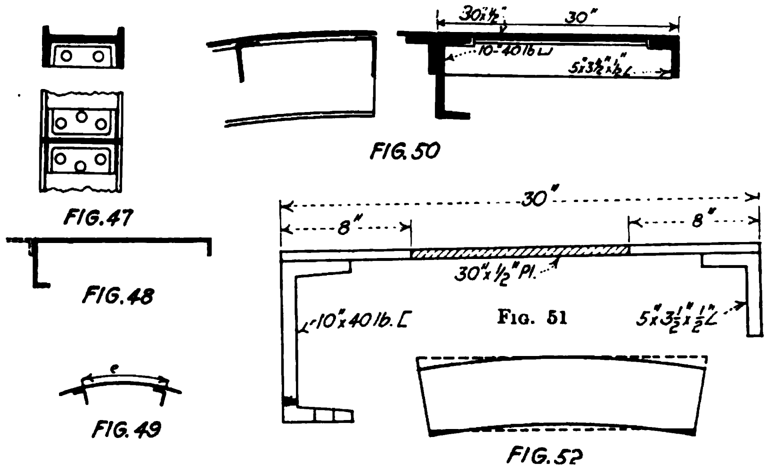


FIG. 47.—Cross section of rolled steel lining used at Kiel (G-8).
FIG. 48.—Suggested cross section of structural steel lining.
FIG. 49.—Structural steel lining, skin stiffeners.
FIG. 50.—Structural steel lining.
FIG. 51.—Structural steel lining designed to meet requirements of example.
FIG. 52.—Wood lining—method of cutting a segment or "cant."

Germany. Figure 47 shows the cross-section of the rolled steel lining used for a canal tunnel at Kiel (G-8). The external diameter of this tunnel is about 11 ft. Each ring, which has a width of 9⅞ in., is made of four segments and the connections between these segments were made by means of flanges of steel castings riveted to the rolled sections as shown. A similar lining was used for the Elbe tunnel at Hamburg (G-4), which had an outside diameter of about 19 ft. 5 in.

53. Suitability.—Owing to its evident suitability and probable economy the authors have suggested the use of fabricated steel for tunnel linings. In making this suggestion they are following the natural engineering development. Formerly many important structures were made of cast iron, including bridges and columns, now structural steel is the material used. At the time cast iron was introduced for tunnel linings this material was the

standard for engineering structures, but at the present time with the high development of the art of manufacturing and fabricating structural steel, this material should be considered seriously for the use of tunnel linings. Structural steel has many qualities that makes it preferable to cast iron, the principal of which in this connection are its greater tensile strength and its greater reliability. The only quality that is questioned by some is its resistance to corrosion, but as regards this the authorities differ in opinion. Under any circumstances the lining may be protected against corrosion by the use of rust-resisting coatings or of non-rusting steel. Tunnels of structural steel will weigh less than those of cast iron and the larger the diameter, the more marked is the difference in weight. The segments, therefore, may be made in larger sizes without increasing the weight of the individual segment beyond that of a cast iron segment for a similar tunnel. The flexibility of the fabricated steel permits it to be drifted into position when being erected. It is not necessary, therefore, to limit the length of the segments on this account as in cast iron lining, and the play of the bolt holes may be reduced materially, insuring greater stiffness of the structure.

54. Details of Design.—Generally speaking the cross-section should be T-shaped in order to obtain the largest section modulus with the least material. Usually it will be found that a cross-section as shown in Fig. 48 is the most suitable. The flange at the one end is made shallow and is used for connecting the segment to the adjacent ring and the other flange forms the structural member. The latter flange may be made of a channel, or two angles or two angles and a plate. The adjoining segments of a ring may be connected with splice plates and no cross flange is necessary, except possibly a small angle for convenience of erection. If the cross joints are staggered it will frequently be found that the angle flange will serve as a splice at the outside of the section.

55. Skin.—The skin must withstand the thrust of the shield jacks and the earth pressures. The latter forces produce bending stresses, and to assist the skin in carrying these it should be reinforced generally with stiffeners running parallel to the longitudinal axis of the tunnel. The skin between two stiffeners (Fig. 49) must be able to carry the external loading. If f represents the safe stress in the steel in pounds per square inch, p the external loading in pounds per square inch, e the distance between two stiffeners in

inches and t the skin thickness in inches, then considering the skin as a flat plate between the stiffeners:

$$f = pe^2/2t^2 \tag{32}$$

The stress in the skin parallel to the axis of the tunnel is determined by

$$R/A + pl^2/12S \tag{33}$$

where R is the thrust of the shield jacks in pounds per linear inch of circumference, A the area of the skin, including the effective area of the stiffener, in square inches per linear inch of circumference, p the external pressure in pounds per square inch, l the unsupported length of the skin in inches and S the section modulus of the combined cross-section of skin and its stiffeners per linear inch of circumference.

56. Cross-section.—Equations for the moments and thrusts acting circumferentially on the lining are given in Chap. VII. The cross-section should be so proportioned that the stresses produced do not exceed the safe limit.

57. Connections.—At the time of erection the connections may be made with bolts which may be replaced later with rivets or by welding the joints. The stress in the connections at the cross joints may be determined as shown in par. **27.**

58. Waterproofing.—If the cross-section of the lining is made as shown in Fig. 50, the joint to be waterproofed is close to the outside of the lining and the waterproofing is applied near the entrance of the water. While the joint may be arranged so that the waterproofing may be carried out as in cast iron lining, probably it will be found that the most economical and effective method is by electric line welding of the joint.

59. Fabricating by Welding.—During the last few years the art of welding has made rapid progress. It is quite possible that structural steel tunnel lining may be fabricated economically by the use of spot welding.

60. Example.—Design a Structural Steel lining for the same conditions as stated under Example, par. **47.** (See Fig. 50.)

(*a*) *External Diameter.*—Allow 6 in. for clearance and select a flange depth of 10½ in. The outside diameter will then be

$$D = 18.00 + 0.50 + 1.75 = 20.25 \text{ ft.}$$

(*b*) *Weight.*—The weight of the lining depends on the design, but as a working value the weight may be assumed to be

$$W = 4D^2 + 100D \tag{34}$$

In this case

$W = 4 \times 20.25^2 + 100 \times 20.25 = 3{,}700$ lb. per linear foot.

(c) *Moment.*—(See Chap. VII, par. **31.**)

$M_2 = 19.75(0.31 \times 100 \times 20.25^2 - 0.33 \times 3{,}700) = - 227{,}000$ in.-lb

$M_3 = 19.75(-0.37 \times 100 \times 20.25^2 + 0.34 \times 3{,}700) = + 275{,}000$ in.-lb.

(d) *Thrust.*—(See Chap. VII, par. **32.**)

$N_2 = -0.05 \times 100 \times 20.25^2 - 0.25 \times 3{,}700 - \frac{1}{2}(3{,}420 - 2{,}160)20.25 = 15{,}700$ lb.

$N_3 = -0.35 \times 100 \times 20.25^2 - 0.01 \times 3{,}700 - \frac{1}{2}(3{,}420 - 2{,}160)20.25 = 27{,}200$ lb.

(e) *Skin Thickness.*—Selecting a thickness of ½ in. for the thickness of the skin, the distance between the stiffeners is determined by (see par. **55**)

$$20{,}000 = 30.7e^2/0.5$$

or

$$e = 18 \text{ in.}$$

The stiffener angles are assumed to be 5″ × 3½″ × ½″ L's with an effective area of 2 sq. in. Applying Equation (33) par. **55,** the stress is found to be 15,600 lb. per square inch.

(f) *Cross-section.*—It will be found that a cross-section as shown in Fig. 51 has a least section modulus of 16.7 in. cubed without deducting the bolt hole in the inner flange and a corresponding area of 10.25 sq. in. Deducting the bolt hole the section modulus is 14.9 in. cubed and the area 10 sq. in. In determining these values the portion of the skin shown cross-hatched is not included, because it lies too far from the flange. At the horizontal axis level the stress at the inside of the lining is

$-15{,}700/10.00 + 227{,}000/14.9 = 13{,}630$ lb. per square inch

and at the outside

$-15{,}700/10.00 - 227{,}000/37.3 = -7{,}670$ lb. per square inch

At the bottom point the stress at the inside is

$-27{,}200/10.25 - 275{,}000/16.7 = -19{,}100$ lb. per square inch

and at outside

$-27{,}200/10.25 + 275{,}000/41.8 = 3{,}900$ lb. per square inch

(g) *Connections.*—(See par. **27.**)

The greatest stress at the inside is at horizontal axis level. At this point $B = (227{,}000 - 15{,}700 \times 2)/9.5 = 20{,}500$ lb. per linear

foot of tunnel or 51,200 lb. per ring. With five 1-in. diameter bolts the shear will be 13,000 lb. per square inch.

The greatest stress at the outside is at the bottom:
$B = (275{,}000 - 27{,}200 \times 6.5)/6.5 = 15{,}100$ lb. per linear foot of tunnel or 37,800 lb. per ring. Four 1-in. bolts in the circumferential joint will carry this load.

E. WOOD LINING

61. General Description.—Wood linings for shield driven tunnels are usually built up in rings of a width of the timber used. Each ring consists of a number of segments sawed to shape and placed end to end. It is preferable to use a short key segment that can be inserted from within the ring. The individual segments of a ring are not directly fastened together, but are spliced by means of the segments of the adjacent rings, the joints of which are staggered. The connections are made by spikes or pins driven through the segment into the preceding ring.

62. General Details.—The external surface of the segments is sawed to a circle conforming to the outer circumference of the tunnel. The inner surface, which is usually covered with waterproofing fabric, must for that reason also have a smooth cylindrical surface. In order to economize on the wood this surface, however, is not cut completely out of the stick, but is attained by nailing wedge shaped pieces of wood at each end of the segment, as shown in Fig. 52.

63. Width and Length of Segment.—The segments are most economically made of commercial sizes of timber and the width to some extent is governed thereby. Wider rings reduce the cost of erection and therefore are preferable, providing the cost of the lumber is not disproportionally greater. The length of the segments is usually made rather short in order to avoid the use of large dimension timber and to decrease wastage by sawing.

64. Depth of Segments.—The radial depth of the segments depends on the forces to which the lining is subjected and may be determined by the equations for moments and thrusts given in Chap. VII. It should be noted that owing to the method of connection, only every second ring can be counted on to carry the bending stresses.

65. Fastenings.—Generally steel spikes or pins are used for connecting the segments to the adjacent ring. They should be

driven into holes bored in the segments and the holes should have a smaller diameter than the fastenings. Hardwood treenails may also be used, split at both ends and provided with wedges of hardwood.

66. Stresses in Fastenings.—The fastenings should be sufficient to resist the bending moment in the ring. If M represents the moment per ring and g the distance between the fastenings in the overlap of the segments of two adjacent rings, then the total shear in the fastening at the end of the ring is M/g. The bearing stress of the fastening on the timber should be investigated also and kept within safe limits.

67. Existing Tunnels with Wood Lining.—Wood lining for shield driven tunnels has been confined almost exclusively to the United States. Table VIII shows the characteristics of some of the shield driven tunnels lined with wood.

TABLE VIII.—SHIELD DRIVEN WOOD LINED TUNNELS

Ref. No.	Tunnel	External diameter, feet	Thickness of wood, inches	Character of ground
(A-12)	Chicago Sewer (39th St.)	24.75	8	
(A-34)	Dorchester............	24.16	9	Clay, sand rock
(A-32)	Hulig Ave.............	21.00	8	Clay, sandy clay, sand
(A-33)	Gayoso Ave...........	19.67	6	Clay, sandy clay, sand
(A-23)	Lawrence Ave..........	20.00	8	Clay
(A-15)	Cleveland Sewer.......	15.25	6	Clay
(A-37)	Milwaukee Siphon......	13.00	8	
(A-14)	Mystic River..........	9.33	15	Gravel, boulders, clay
(C-1)	Havana Sewer.........	10.00	6	Clay, sand
(A-36)	West Water Street.....	6.33	5	Sand
(A-20)	Providence............	6.33	6	Dry and wet sand
(A-11)	Malden Bridge.........	5.50	5	
(M-20)	Melbourne............	10.50	note	
(A-38)	Milwaukee Sewer.......	9.33		

NOTE.—The lining for the Melbourne tunnel was fabricated in segments similar in shape to cast iron segments.

68. Example.—Design a wood lining for a circular water intake tunnel in firm waterbearing ground. The inside diameter shall be 16 ft. and it will be provided with an inside concrete lining 15 in. thick. The depth of water is 40 ft., the depth of cover

10 ft. The water weighs 64 lb. per cubic foot and the ground in water weighs 60 lb. per cubic foot. Air pressure 20 pounds per square inch.

(a) *External Diameter.*—Assuming that the thickness of the wood lining will be 9 in., the external diameter will be

$$D = 16 + 2 \times 1.25 + 2 \times 0.75 = 20 \text{ ft.}$$

(b) *Weight of Lining.*—If the wood weighs 45 lb. per cubic foot, the lining will weigh

$$W = \pi(20^2 - 18.5^2)\ 45 = 2{,}000 \text{ lb. per linear foot.}$$

(c) *Value of k.*—The value of the factor k is determined from equation (16) Chap. VII, par. **23**, in which

$w_1 = 64$, $w_2 = 60$, $h_1 = 40$, $h_2 = 10$, $a = 10$, $a_1 = 9.63$, $W = 2{,}000$, $P = 3{,}800$, and $w_1a^2 = 6{,}400$, $w_1(h_1 + h_2)a = 32{,}000$, $(w_1 + w_2)a^2 = 12{,}400$, $Pa = 38{,}000$, $w_2a^2 = 6{,}000$, $w_2h_2a = 6{,}000$, and

$$k = -\frac{6{,}400n_1 + 32{,}000n_2 + 12{,}400n_3 + 2{,}000n_4 + 38{,}000n_5}{6{,}000n_1 + 6{,}000n_2}$$

The constants n are found in Table IV, Chap. VII, par. **19.** At the bottom they are $n_1 = -0.29$, $n_2 = -0.25$, $n_3 = 0.04$, $n_4 = 0.06$, $n_5 = 0.25$, and

$$k_3 = \frac{-1{,}856 - 8{,}000 + 496 + 120 + 9{,}500}{1{,}740 + 1{,}500} = \frac{260}{3{,}240} = 0.08$$

This value is less than 0.50, and the latter value must, therefore, be used in determining the moment.

(d) *Moment.*—The moment is determined by equation (11), Chap. VII, par. **19.**

$$M_3 = 115.5(-0.5 \times 3{,}240 + 260) = -157{,}000 \text{ in.-lb.}$$

(e) *Thrust.*—The thrust is determined by equation (15) Chap. VII, par. **22.** It is assumed that the air pressure is 20 lb. per square inch.

$$N_3 = -10 \times 64(13.3 + 40 + 10) - 0.5 \times 10 \times 60(13.3 + 10) + 2{,}880 \times 10 = -18{,}700 \text{ lb.}$$

(f) *Unit Stress.*—Assume a permissible stress of 1,400 lb. per square inch. As only every second ring can take tension the tensile stress may be taken at 700 lb. per square inch. Let t = the thickness of the wood lining in inches, then

$$700 = -\frac{18{,}700}{12t} + \frac{157{,}000}{2t^2}$$

or

$$t = 9.5 \text{ in.}$$

Without air pressure the maximum compression is

$$s = -\frac{47,500}{114} - \frac{157,000}{180.5} = 1,287 \text{ lb. per square inch.}$$

(*g*) *Jack Pressure.*—Assuming the jack pressure to be 12,000 lb. per square foot of face, or a total of 3,770,000 lb., the pressure will be

$$\frac{3,770,000}{231.5 \times \pi \times 9.5} = 550 \text{ lb. per square inch.}$$

(*h*) *Fastenings.*—Assuming the overlap of the segments in adjacent rings is 27 in., the fastenings may be placed 15 in. apart. If they consist of two 1-in. diameter steel pins at each end, the shear in the steel pins will be 6,700 lb. per square inch and the bearing on the wood 440 lb. per square inch.

F. MASONRY LINING

69. Materials.—A masonry lining may be made of brick, laid in mortar; cut stone or precast concrete blocks, laid dry or in mortar; or of concrete cast in place. All of these kinds of masonry have been used, but for shield driven tunnels linings of masonry laid in mortar are now rarely used and would usually be uneconomical compared with concrete. Concrete is used either cast in place or in the form of precast concrete blocks.

70. Strength.—As previously stated, the primary lining for a shield driven tunnel must be able to carry the external loading immediately after erection. Concrete cast in place is not able to do this and the external loads must be carried on formwork until the concrete is set and has obtained sufficient strength. Actually, therefore, the formwork comprises the primary lining and it must be able to carry not only the weight of the concrete, but also the earth pressures. If the calculations show that tensile stress will occur, steel reinforcement must be used. Tensile stresses can be avoided by making the lining of sufficient thickness, and this is generally preferable to the use of reinforcement.

71. Waterproofing.—It is generally required that the completed lining shall be waterproof, but this is a difficult matter to obtain in concrete, particularly if the tunnel is under a head of

water. It may be possible to make the lining reasonably watertight by using a proper mixture. It may also be helped by careful placing of the concrete, but this is difficult in the confined working space immediately behind the shield. The surest way to obtain a watertight concrete lined tunnel, whether made of concrete cast in place or of precast blocks is to cover the inside of the concrete lining with a waterproofing material and to build an inside protection for this waterproofing. Skilful and persistent grouting may also procure a watertight concrete.

72. Thrust of Shield Jacks.—The shield jacks are usually arranged so that they bear against the lining just erected. This is not satisfactory when the lining is built up of masonry laid in mortar or of wet concrete, although this has been done in some cases. In the Gowanus flushing tunnel (A-22), for example, the jacks pressed against a cast steel ring bearing against the new brickwork. In the Cleveland intercepting sewer (A-15) a similar method was used for part of the work and the brickwork damaged by the jacks was relaid each day.

73. Support on Forms.—In the early roof shields the jacks were arranged so that their thrust was carried by the formwork inside the tunnel instead of on the lining proper, but the thrust that could be carried in this manner was limited. In order to distribute the pressure over a large distance, longitudinal push bars were provided between the centerings on line with the shield jacks.

74. Support on Push Bars in Concrete.—In the construction of the Tremont Street tunnel at Boston (A-10), which was lined with concrete cast in place, the method of inserting iron push bars in the concrete was first introduced. The principle is to relieve the soft concrete from the thrust of the shield jacks by letting it be carried by continuous bars placed parallel to the axis of the tunnel on line with the shield jacks. As the work progresses new lengths of bars equal to the length of the advance of the shield are added and incorporated in the concrete. The push bars should be faced at both ends and be provided with means to connect them with the previous lengths.

75. Support on Wet Concrete.—Another method, used with wet concrete, involves confining the concrete at the forward end by means of timbers cut to shape and covering the space between the form and the tail of the shield. The shield jacks press against these timbers and the immediate result is a compression of the

concrete. Not until the concrete is sufficiently compressed to develop the necessary reaction will the shield start to move forward. This method was first used on the Siphon de l'Oise (F-5) but not with great success. The concrete was confined between an inner and outer form. The method has been further developed and patented by a German firm which has built several tunnels with complete success. By their method no outer form is used so that, when the shield starts to move forward, the concrete is forced into the space formerly occupied by the tail of the shield, filling it completely, and thereby reducing to a minimum the possibility of a settlement. The compression of the concrete also increases the watertightness of the lining. It is necessary to use fairly slow setting concrete in order to avoid an initial set before the pressure has been applied and in open ground there is a possibility of the air pressure driving the water out of the concrete before it has set.

76. Concrete Blocks.—Precast concrete blocks for the lining of shield driven tunnels must be capable of carrying the thrust of the shield jacks and may be provided with means for holding the blocks together longitudinally. Several patented designs of concrete blocks are in existence, the principal claims of which relate to the methods of obtaining these requirements.

77. Example.—Design a concrete sewer through firm water-bearing ground, having an elliptical cross-section with the internal horizontal diameter 16 ft. long and the internal vertical diameter 10 ft. long. No water above the ground, but the ground waterbearing from the surface, the cover above the tunnel being 30 ft. Weight of water 64 lb. per cubic foot and weight of earth in water 60 lb. per cubic foot.

(*a*) *External Diameter.*—Assume provisionally that the thickness of the concrete is 2 ft. The horizontal radius is then $a = 10$ ft. and the vertical radius $b = 7$ ft.

(*b*) *Weight of Lining.*—With this assumption the weight of the lining will be

$$W = 140\,\pi\,(70 - 40) = 13{,}200 \text{ lb. per linear foot of tunnel.}$$

(*c*) *Value of Factor k.*—From equation (16), Chap. VII, par. **23**, the value of k is now determined as follows:

$$w_1a^2 = 6{,}400;\ w_1(h_1 + h_2)a = 19{,}200;\ (w_1 + w_2)a^2 = 12{,}400;$$
$$Pa = 37{,}200;\ w_2a^2 = 6{,}000;\ w_2h_2a = 18{,}000$$

and

$$k = -\frac{6{,}400n_1 + 19{,}200n_2 + 12{,}400n_3 + 13{,}200n_4 + 37{,}200n_5}{6{,}000n_1 + 18{,}000n_2} = 2.7$$

This value is greater than 2.00, and the latter value should be used in determining the moment.

(*d*) *Moment.*—The moment is now determined by equation (11), Chap. VII, par. **19.**

$$M_3 = (-2 \times 2{,}520 + 6{,}900)108 = 201{,}000 \text{ in.-lb.}$$

(*e*) *Thrust.*—The corresponding thrust is determined from equation (15), Chap. VII, par. **22.**

$$N_3 = -7 \times 64 \times 43.3 - 2 \times 7 \times 60 \times 43.3 = -55{,}800 \text{ lb. per linear foot.}$$

(*f*) *Stress.*—Let the permissible stress be 400 lb. per square inch, then the thickness t is determined by

$$400 = -\frac{55{,}800}{12t} + \frac{201{,}000}{2t^2}$$

or

$$t = 23 \text{ inches.}$$

Assuming an air pressure of 20 lb. per square inch, the maximum tensile stress is determined by,

$$s = \frac{-35{,}700}{276} + \frac{201{,}000}{1{,}058} = -60 \text{ lb. per square inch.}$$

There is, therefore, no tensile stress at the bottom.

CHAPTER IX

TUNNEL SHIELDS

A. GENERAL DESCRIPTION

1. Purpose and Requirements of Shield.—As described in Chap. III, tunnelling in loose ground by mining methods involves much and costly timbering. The principal purpose of a tunnel shield is to replace the heavy supporting timbering, but as a general rule it does not obviate the work of excavating nor of sheathing the excavation. The shield, therefore, must be arranged so that there is access to the face in front of the shield, where the work of excavation is carried out; the length excavated must be short, so that little or no timbering is needed around the periphery; the shield must be capable of being moved forward as the work progresses; and the shield must cover the excavation until the lining is erected.

2. General Description of Shield.—A tunnel shield (see Fig. 53) consists essentially of a horizontal cylinder A, called the skin; an internal structure F and hydraulic jacks E. The forward part of the shield D is called the cutting edge and the rear part, which consists of the skin only, is called the tail. The hydraulic jacks are arranged close to the skin, parallel to the longitudinal axis of the tunnel; when onep they extend into the tail space.

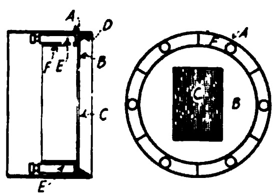


FIG. 53.—The tunnel shield—main parts.

3. Method of Use.—The procedure in shield tunneling is, first to excavate a length ahead of the shield equal to the width of one ring of the tunnel lining; next to push the shield forward the distance excavated by means of the jacks reacting against the lining already erected; then to draw back the plungers of the jacks into their cylinders to make room for the erection of the lining; and finally to erect a ring of the lining in the clear space within the tail of the shield. The construction of the tunnel is completed by repeating again and again this sequence of operations.

4. Effect of Size and Nature of Ground.—While in general principles the design of the shield is the same whatever the size of the tunnel or the nature of the ground, these factors affect the design of the internal structure. In all cases this includes

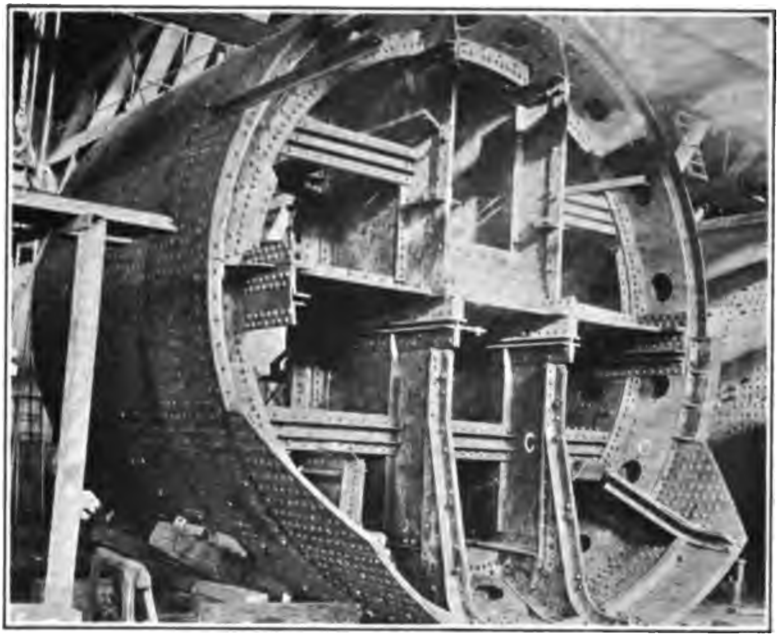


FIG. 54.—A tunnel shield being assembled in the shops; to show the framing of a large shield. This shield is turned upside down, hence the hood is at the bottom. (Courtesy of *Hudson and Manhattan Railroad.*)

an annular structure stiffening the skin and extending from the cutting edge to the tail. If the shield is small and the ground good, this may form the whole internal structure, or there may be a transverse diaphragm "B" in Fig. 53 immediately behind the cutting edge with an opening *c* affording access to the face. If the diameter of the shield is 13 ft. or more there is room to introduce horizontal or vertical bracing, or both, and still retain openings large enough for convenient access to the face (see Fig. 54 (A-6)). Such bracing adds greatly to the strength of the shield, divides it into convenient working chambers and affords means for attaching the various appliances with which such shields are furnished.

5. Water Traps.—In open waterbearing ground to protect the tunnel against a sudden inrush of water the shield may be provided with a water trap (Fig. 55). The trap is made by dividing the diaphragm in two parts, at or near the level of the horizontal diameter, and setting the lower part behind the upper. By this means the opening is made horizontal instead of vertical and the water cannot enter through such an opening, if the air pressure is high enough. The arrangement as described is suitable for small shields only. In larger shields with more than one working level such a trap would interfere seriously with the work of excavation and would make improbable the rescue of the men working in front of the shield, if a bad blow occurred. In some large shields, for example the Rotherhithe tunnel (E-17) shield, traps as described were provided at each working level, (see Fig. 56), but it is apparent that the efficacy of this construction depends on the upper traps being closed immediately and tightly, when a serious blow occurs. Otherwise the air will escape through these traps while the water will enter at the lower levels, and not until the water has reached the uppermost level will the trapping become effective. The necessity for traps, however, is greater in a small shield, because here there is little chance for the men to escape, but in a larger tunnel, while this may be flooded, there exist means, as will be described in another chapter, to provide an escape for the men.

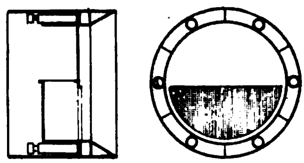


Fig. 55.—The water trap as applied to a shield.

6. Examples of Shields.—Figure 56 shows diagrammatically the arrangement of various shields used on previous work. Figure 57 shows the rear face of a small shield with the erector removed. Note that this shield is provided with openings which may be closed (doors not shown), while Fig. 58 shows an open shield.

B. DETAILS OF SHIELD STRUCTURE

7. Diameter of Skin.—The diameter of the skin is determined by the diameter of the tunnel lining, which is erected within the cover of the tail. A certain clearance is necessary between the

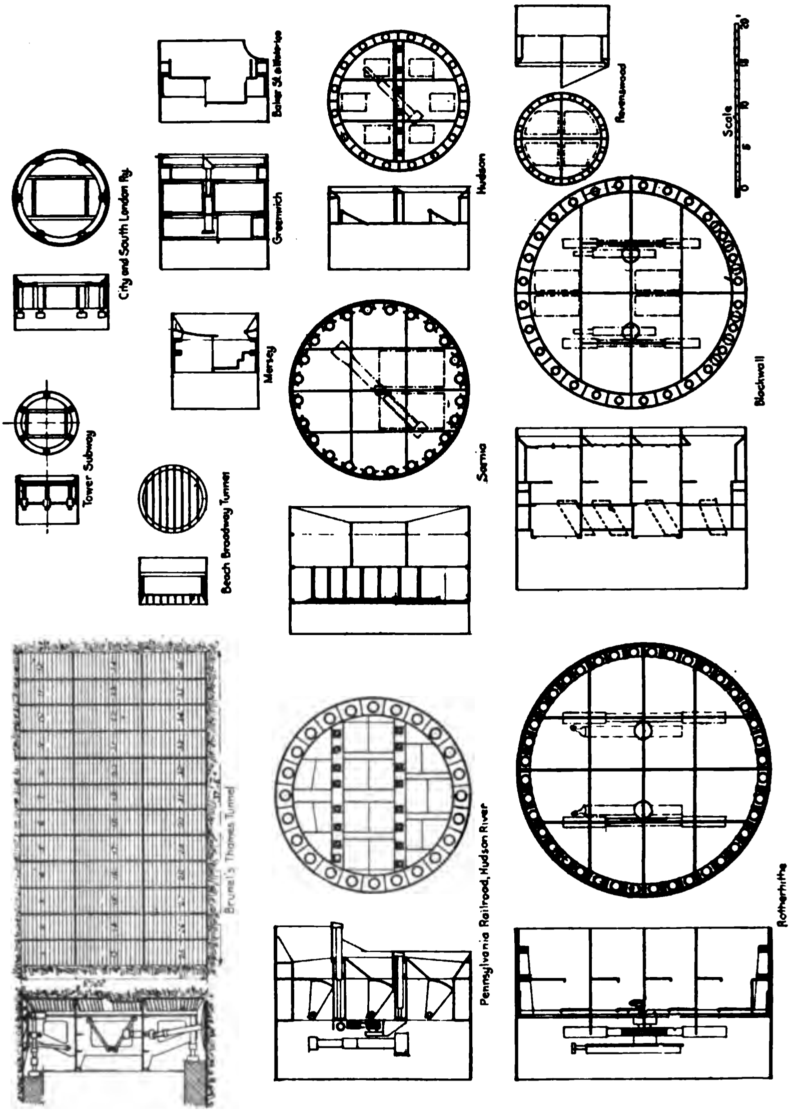


FIG. 56.—Some actual shields. Diagrammatic longitudinal and cross sections.

FIG 57.—Rear view of shield with erector removed. (Courtesy of *Hudson and Manhattan Railroad.*)

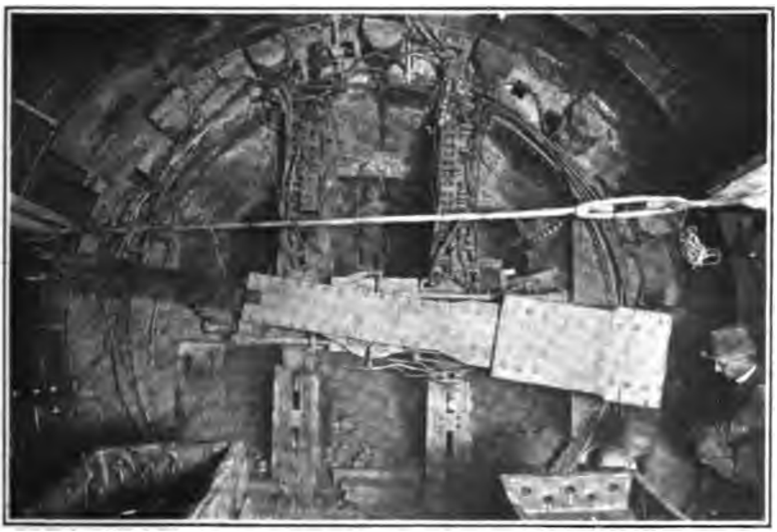


Photo. by P. P. Pallis.

FIG. 58.—Rear view of shield of open type. (Courtesy of *New York Transit Commission.*)

outside of the lining and the inside of the tail, partly to facilitate erection and partly to permit deviation of the direction of the axis of the shield from that of the tunnel lining. This latter necessity not only exists when the tunnel is on a curve, but is continuous throughout the driving of the tunnel, owing to the impossibility of keeping the shield on exact line and gradient. The erection clearance required is determined by judgment, while that for deviation is a function of the diameter d of the lining, (see Fig. 59), the overlap m of the lining on the tail and the lead l, which may be expressed as the difference between the maximum and minimum distances between the face of the lining and a transverse plane of the shield. The clearance x may be expressed by

$$x = ml/d \tag{35}$$

This equation represents the minimum clearance required, but as stated above, additional clearance is necessary for convenience of erection. An average lead is $d/80$.

8. Clearances of Shields in Constructed Tunnels.—As a guide in determining the proper clearance, the clearances used for various shield driven tunnels are shown in Table IX. The Table shows that the average value of the clearance is about 0.8 per cent of the outside diameter of the lining, or in other words, the usual practice has been to make the inside diameter of the tail equal to 1.008 times the outside diameter of the lining. The Table also shows the excess excavation necessitated by the larger diameter of the shield in percentage of the displacement of the lining. It shows that the mean excess excavation has been about 4½ per cent.

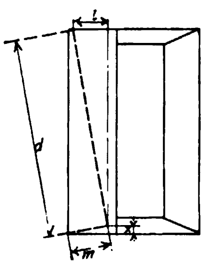


FIG. 59.—Clearance between skin of shield and tunnel lining.

9. Small Clearances Preferable.—The clearance between the skin and the lining increases the volume of excavation and of subsequent refilling behind the lining. In addition, when the work is carried out in compressed air, it constitutes a source of heavy leakage of air. The clearance should be kept, therefore, as small as the conditions will permit. It will help materially to reduce the necessary clearance, first, to use a lining which has a true and smooth exterior surface, and, second, to have a competent foreman to direct the movements of the shield according to the

TABLE IX.—TAIL CLEARANCE IN SHIELDS OF EXISTING TUNNELS

	Tunnel	External diameter of lining	External diameter of tail	Thickness of tail	Internal diameter of tail	Clearance	Clearance, per cent of external diameter of lining	Excess excavation per cent
(E-4)	Mersey	10′ 0″	10′ 3″	¾″	10′ 1½″	1½″	1.25	5.06
(A-8)	Ravenswood	10′ 10″	11′ 0¾″	⅞″	10′ 11″	1″	0.77	4.28
(S-2)	Glasgow District	12′ 0″	12′ 2½″	½″	12′ 1½″	1½″	1.04	3.50
(E-13)	Lea	12′ 3½″	12′ 7″	1″	12′ 5″	1½″	1.02	4.62
(E-9)	Central London	12′ 6″	12′ 8″	½″	12′ 7″	1″	0.67	2.68
(E-11)	Greenwich	12′ 9″	13′ 0″	1″	12′ 10″	1″	0.65	3.96
(E-15)	Baker St. & Waterloo	12′ 9¾″	13′ 0″	½″	12′ 11″	1¼″	0.81	2.95
(A-16)	Battery	16′ 8½″	16′ 11¼″	1⅛″	16′ 9″	½″	0.25	2.76
(A-21)	Steinway	16′ 10″	17′ 3″	1½″	17′ 0″	2″	0.99	5.01
(S-1)	Glasgow Harbor	17′ 0″	17′ 3″	1″	17′ 1″	1″	0.49	2.96
(A-27)	Old Slip	17′ 6″	18′ 0″	2¼″	17′ 7½″	1½″	0.71	5.80
(A-30)	14th Street	18′ 0″	18′ 5½″	2″	18′ 1½″	1½	0.69	5.10
(A-28)	Whitehall	18′ 0″	18′ 6″	2¼″	18′ 1½″	1½″	0.69	5.63
(A-35)	60th Street	18′ 0″	18′ 6⅞″	2 7/16″	18′ 2″	2″	0.92	5.63
(A-6)	Hudson	19′ 6″	19′ 11″	1¼″	19′ 8½″	2½″	1.07	4.32
(A-18)	Pennsylvania Railroad Hudson River	23′ 0″	23′ 6¼″	2⅛″	23′ 2″	2″	0.72	4.58
(A-19)	Pennsylvania Railroad East River	23′ 0″	23′ 6½″	2¼″	23′ 2″	2″	0.72	4.77
(F-12)	Concorde Metropolitain	25′ 6″	26′ 1″	2¼″	25′ 8½″	2½″	0.82	4.52
(E-7)	Blackwall	27′ 0″	27′ 8″	2½″	27′ 3″	3″	0.92	4.99
(E-17)	Rotherhithe	30′ 0″	30′ 8″	2¼″	30′ 3½″	3½″	0.97	4.49
					Mean		0.81	4.44

instructions of the engineer, whose lines and levels should always follow close behind the shield.

10. Beading around Tail.—In some shields the clearance at the end of the tail has been reduced by riveting a circumferential beading, generally a flat plate, inside the tail at its extreme end. By this arrangement the width of the annular space is reduced while the necessary working space may be retained. It has the effect of decreasing the source of leakage of air, but it does not reduce the additional volume to be excavated and refilled. Beadings are useful, but are easily stripped off. In fact, as a general rule, any projection inside of the portion of the tail occupied by the lining, is inadvisable. Almost invariably it will be stripped off before the shield has moved far.

11. Length of Tail.—The length of the tail depends primarily on the width of the ring of the tunnel lining, that is to say, the tail must be long enough to permit the erection of a ring and still retain an overlap on the lining previously erected. In addition the tail should be long enough to allow a plunger of the shield jacks to be removed without exposing the ground. In some cases the tail has been made long enough to cover two ring widths and part of a third. The advantage of this is that if a segment of the ring just erected should break under the pressure of the jacks pushing directly against it, the segment could be removed at the end of the shove under cover of the tail. A long tail is desirable on account of the protection it affords, but the tail is the weakest part of the shield structure and, if bent or damaged, is difficult to repair. Furthermore, the total length of the shield is increased as the tail is increased in length, and as the proper guiding of a shield is more readily accomplished when the tail is short, it is advisable to make the tail as short as the conditions will permit.

12. Construction of Skin.—Usually the skin is made of one or more thicknesses of steel plate of a single width from front to back and in as many pieces circumferentially as the size of the shield requires. The skin should be thick enough to support the earth pressures without sensible deformation at the tail where it has no internal support. As cover plates are objectionable both outside of the skin and inside of the tail it is generally good practice to make the skin in several thicknesses of plates, staggering the joints so that the plates of one layer are spliced by those of the other layers, as shown in Fig. 60, which represents one of the eight sections of the skin for a small diameter tunnel. The skin in this case is

made of three layers of plate, except in the middle portion, where only two layers are used with splice plates to cover the inner joint. This design is not usual but is worth following. The portion with two plates only is that occupied by the internal structure and may be amply supported, so that the full thickness of skin is not needed here, and by leaving out this inner plate it is possible to bring the shield jacks so much closer to the outside of the lining and thereby reduce the inevitable eccentricity of the jack pressure on the cast iron lining.

13. Welding.—Figure 60 indicates the large number of rivets, many of which are countersunk on both sides, needed for assem-

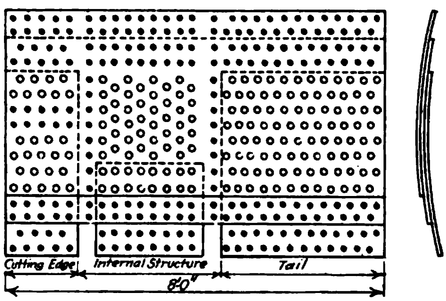


FIG. 60.—One section of shield skin for a small tunnel.

bling the skin of a shield. The art of welding structural steel has developed greatly during recent years and it is reasonable to expect that much or all of this riveting as well as that for other parts of the shield structure in the future will be replaced by welding, giving greater strength, less work of erection and lessened cost.

14. Cutting Edge.—By the cutting edge is understood the annular structure of the shield at its extreme front. As this part of the shield is subject to the first severe head-on contact with such obstacles as may be in the way of the shield, it must be strong enough to receive such shocks without serious damage. The importance of this is illustrated by an accident that happened to the shield of the Blackwall tunnel (E-7) under the River Thames. The cutting edge of this shield consisted simply of the skin plates reinforced about 12 in. from the front edge by inclined plates. By driving the bottom part of the cutting edge against large pieces of rock, embedded in the ground, it collapsed and it was necessary to drive a heading 19 ft. wide in advance of

the shield. In this heading a concrete cradle was built for the shield to slide upon, but to keep it dry enough to work in another heading had to be driven at the top to intercept the water. (*Proc. Inst. C. E.*, vol. 130, p. 65.)

15. Construction of Cutting Edge.—For strength the cutting edge is made wide at the back, but for convenience of excavation it usually tapers toward the front as shown in Fig. 61.

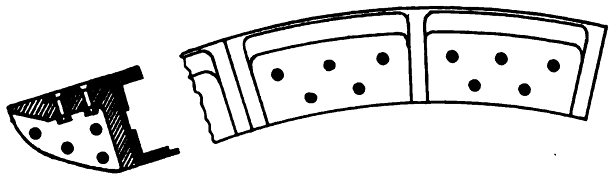


Fig. 61.—The cutting edge of a shield.

In some shields the front portion, or shoe, of the cutting edge consists only of the skin plates as in the case of the Blackwall tunnel shield just described. More often the shoe is made of castings of iron or steel. The best construction is obtained

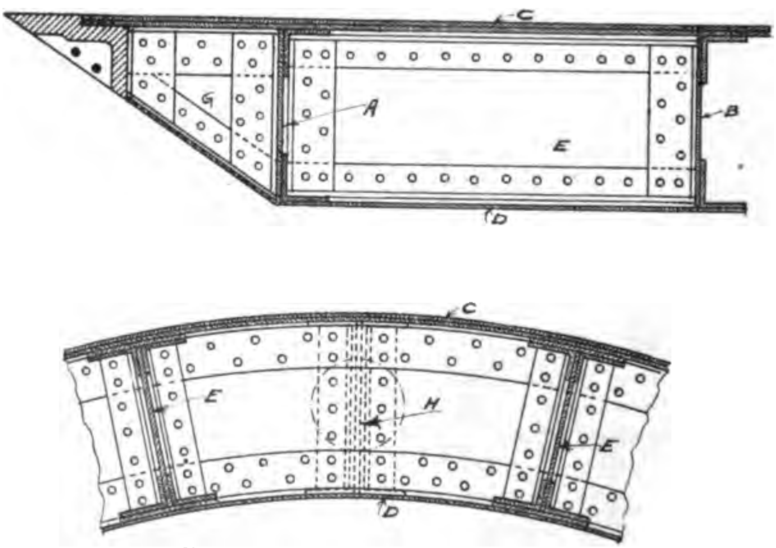


Fig. 62.—The cutting edge of a shield.

by making the shoe of steel castings in segments with machined joints, bolted together and to the shield structure (Fig. 61). If any damage is done to such a shoe the broken segments may be replaced without much difficulty.

16. Length of Cutting Edge.—In open shields the cutting edge need consist only of the shoe, but in shields where the diaphragm interferes with free access to the whole face, the cutting edge should be long enough to permit a man to work under its

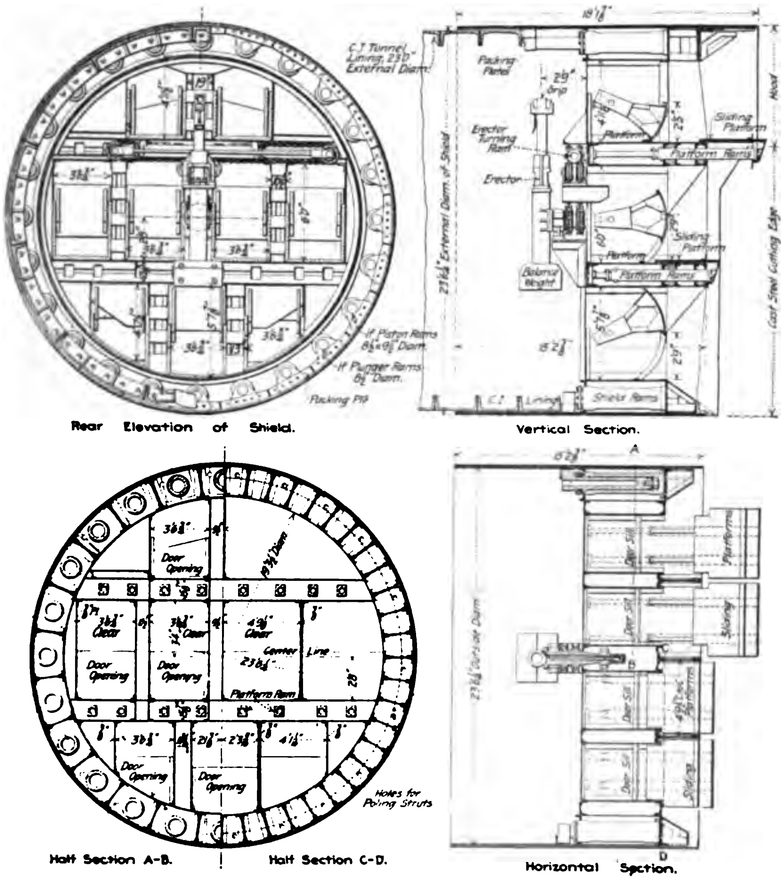


FIG. 63.—Pennsylvania Railroad Hudson River Tunnel (A-18). Arrangement of shield. (From *Eng. News*, Dec. 13, 1906.)

cover in front of the diaphragm. In that case the cutting edge will consist of the front part of the skin of the shield, reinforced and supported by brackets to the internal structure of the shield, and provided with a shoe of steel castings (Fig. 62). In order to work unhampered the length of the cutting edge in front of the diaphragm should not be less than 3 ft. and 4 ft. would be a better length.

17. Hood.—The hood of a shield is a forward extension of the circumferential structure of the shield. The extension may be of a uniform length (see Figs. 63 and 64 (A-18) and (E-15)) and in that case it extends over the roof and part of the sides only, or it may be sloping from top to bottom (see Fig. 65), having the greatest length at the top. The first type was evolved in connection with the use of "clay pockets" for the purpose of avoiding timbering around the periphery of the excavation, as is more

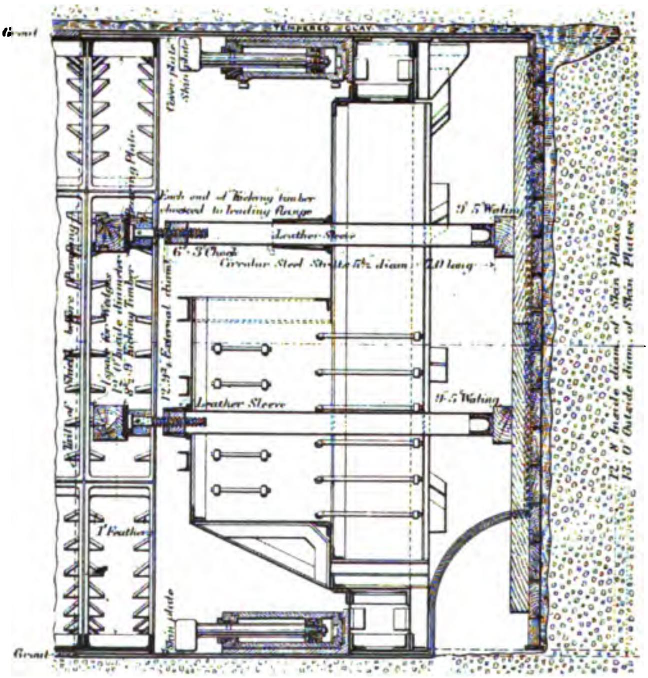


FIG. 64.—Baker Street & Waterloo Railway Tunnel (E-15). Longitudinal section through shield. (From *Proc. Inst. C. E.*, vol. 150.)

fully described in Chap. XII. It has been found useful also where the lower part of the excavation is in rock and the upper part in loose ground, because it facilitates excavating the loose ground ahead of the rock, thus decreasing the danger of disturbing the support of the loose ground by the blasting of the rock. In this case, when the ground through which the shield is driven changes in character along well defined lines, the hood may be useful for a certain part of the work, but entirely unsuitable for the remainder. The hood may then be made detachable, as on

the shields of the Pennsylvania Railroad tunnels under the Hudson River (A-18), which will be described more fully in par. **91** of this chapter.

18. Sloping Hood.—The purpose of the sloping hood is to conform the front of the shield to the natural slope of the ground so so as to avoid supporting the face of the excavation. While this arrangement is sound in principle and is workable where the slope of the excavation is steep, it does not work out satisfactorily in ground which has a flat natural slope, and it is in such ground that it is most needed, because here the timbering of a vertical face is most difficult. The reason for this is that in such ground it is almost impossible to prevent the ground from flowing in from below the shield, thus causing the shield to settle and this is highly aggravated by a heavy overhang of the top of the shield.

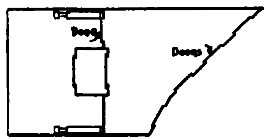
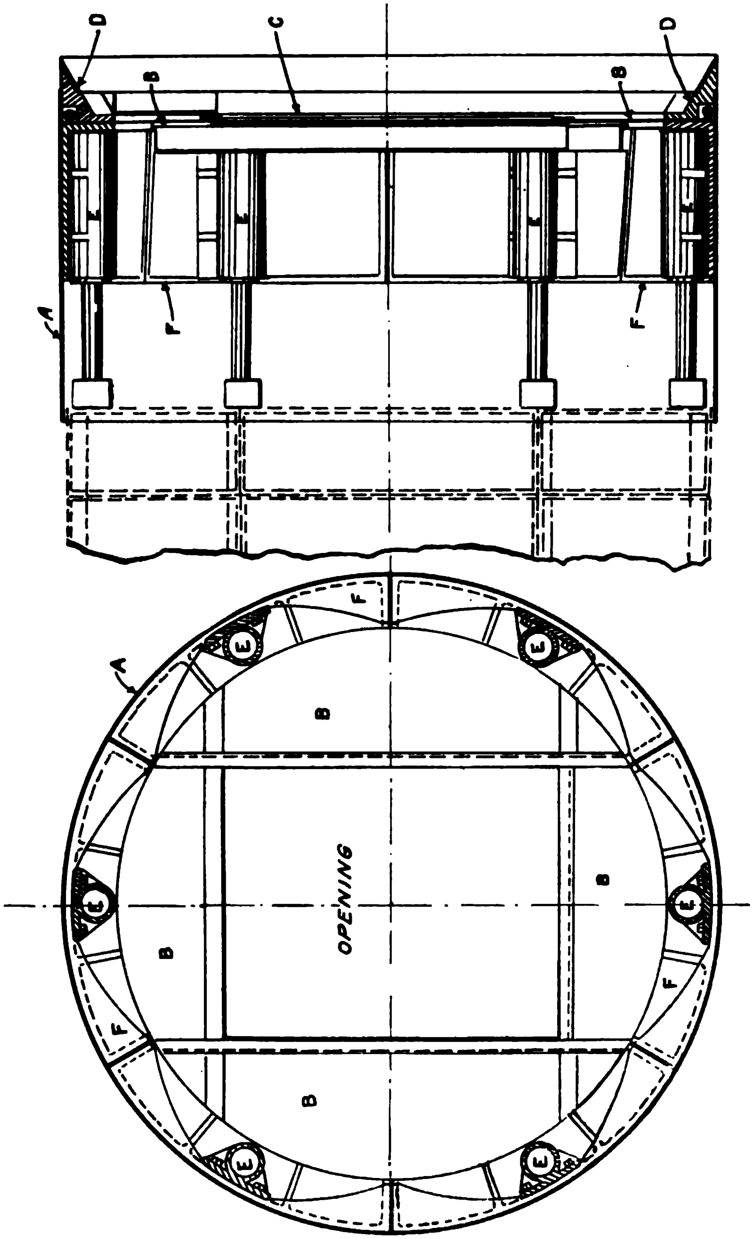


Fig. 65.—Longitudinal section of shield with sloping hood or "Visor." Used for tunnel under River Spree, Berlin (G-1).

19. Extensible Hood.—In some cases an extensible hood, consisting in fact of a series of steel polings, has been used. The polings have been attached to the shield in such a manner that they could slide forward, one by one, and could be forced into the ground under the pressure of hydraulic or screw jacks. The purpose has been first to force these polings into the ground, then to carry out the excavation under their cover and finally to move the shield forward while the polings remain stationary. There has been usually the practical difficulty, however, that the shield rarely follows the same straight path in which the polings have been driven, causing the latter to buckle and destroying their usefulness.

20. Internal Annular Structure, Greathead Shield.—The internal structure of the small diameter Greathead shield, used extensively in England and other places, consists of a short cast iron cylinder, "*F*," fitting closely inside the skin and made in segments (see Fig. 66). The segments are flanged on all four sides, the end flanges being used for bolting the segments together and the circumferential flanges to give stiffness to the structure. The front circumferential flange, which has a uniform depth, is used also for connecting the cylinder to the diaphragm. Between the flanges of adjacent segments, which are machined, are



Elevation of Shield—Rear View. Longitudinal Section.

FIG. 66.—Greathead shield for small diameter tunnel in London clay.

placed packing strips of hardwood so as to insure close fit against the skin. The shield jacks have their bearing on these castings to which they are bolted. The rear flange of the cast iron cylinder is partly cut away to permit the extension of the jacks. This construction is not as rigid as might be desired. It is stated (Copperthwaite, 1906, p. 106), in connection with the Central London Railway shields, which were made of this construction: ". . . the shields, as a general rule, kept fairly rigid, although all to a more or less marked degree widened in the horizontal diameter with a corresponding flattening of the vertical height."

21. Larger Shields with Cast Stiffening Structure.—In England the cast iron stiffening cylinder has been used not only for shields of small diameter, but also in larger shields. The construction for such shields is in principle the same as for the smaller shields. The cross bracing is bolted to the castings.

22. Rotherhithe Tunnel Shield.—An interesting variation is presented by the Rotherhithe tunnel shield (see Fig. 56 (E-17)) which had an outside diameter of 30 ft. 8 in. The steel plate skin was omitted except at the tail, and the internal stiffening cylinder and cutting edge, which were made of steel castings, consisted of three segmental rings, held together by bolts and dowels through the circumferential flanges, and the tail was attached to the rear ring. A construction similar in principle, of the envelope made in rings, was used for the Sarnia tunnel (see Fig. 56 (A-5)) in which case, however, the rings were of structural steel. The want of continuity of this construction exposes the shield to damage and it cannot be considered as satisfactory as that described in par. **12** of this chapter.

23. Structural Steel Stiffening Ring.—In shields built in the United States and to some extent also in shields of British make, the stiffening ring is made of structural steel instead of cast iron as above described, whereby a stiffer structure may be obtained. Figure 62 shows the usual construction. Two annular web plates *A* and *B* are riveted through angles to the skin of the shield *C* and to an inner skin *D*. The annular box-girder thus formed is stiffened by diaphragms *E* spaced uniformly around the circumference. The compartments formed in the box-girder by the diaphragms are used for housing the shield jacks, which are inserted through openings in the rear web plate. The diaphragms are continued in front of the forward annular web plate as reinforcing brackets *G* for the cutting edge, and similar brackets, *H*,

are placed between them to assist in taking the thrust of the shield jacks.

24. Size of Box-girder.—As the compartments of the box-girder are used for housing the shield jacks, which are inserted from the rear, the depth of the annular web plate must be large enough to permit a hole being cut in it of sufficient size to let the jack enter without unduly weakening the girder construction. The width of the box-girder is determined by the length of the jacks, which when inserted should have only the stuffing box of the cylinder extending outside of the box-girder.

25. Strength of Connections.—The shield jacks bear against the forward plate of the box-girder and the stress is transmitted through riveted connections to the skin. These connections must be sufficient to carry the maximum pressure that may be developed by the jacks. Except, however, where definite loads come upon the structure the dimensions of the members forming the shield structure cannot be computed. It is more a matter of proportioning them according to judgment in such a manner as to obtain a strong, rigid structure which will stand up under all the heavy service to which the shield may be subjected. During the driving, when no other means will make the shield behave as desired, brute force is applied regardless of the niceties of previous computations.

26. Internal Cross Bracing.—In shields of a size large enough to permit more than one opening to the face, cross bracing should be provided to strengthen the structure. Usually the cross bracing will consist of a plate girder construction, either with a single or a double web, extending from the rear of the annular box-girder to the front of the cutting edge. The horizontal stiffening members serve in addition as working platforms, and both the vertical and horizontal members are convenient for attaching—or if of box-girder construction, for housing—the various appliances used in connection with the shield as will be described hereafter (see Fig. 58).

27. Spacing of Stiffening Girders.—The horizontal stiffening girders should be spaced, if possible, so that a man may stand upright, because otherwise his working efficiency is decreased. The minimum headroom, therefore, should not be less than 6 ft. The vertical stiffening girders should be spaced sufficiently to permit unobstructed working, or not less than 3 or 4 ft. in the clear. If part of the pocket formed by the horizontal and vertical

girders is used for passageway only, this part may be made narrower than that which is used as a working chamber. If the shield is to be carried through rock for any appreciable distance, it is most desirable to design the shield so that one of the bottom pockets will be large enough to permit the passage of a muck car on a track laid through the shield to the face where the work of excavation is in progress.

28. Transverse Diaphragm.—The transverse diaphragm shown in Fig. 53 serves the double purpose of stiffening the structure and of providing a means of protecting the face. For the first purpose the diaphragm is particularly advantageous in shields with only one opening, while in larger shields the cross bracing performs this duty to a great extent. The use of the diaphragm as a protection of the face is largely dependent on the character of the ground. The construction of the diaphragm will depend, therefore, on the size of the shield and the character of the ground.

29. Diaphragm in Small Shields in Dry Ground.—In the original Greathead type of shield the diaphragm consisted of a circular plate, placed immediately behind the cutting edge, with a rectangular opening for giving access to the face (see Fig. 66). The opening was reinforced around the edges with flat bars at the top and with channels at the sides and bottom. The purpose of using channels was to form guides into which square timbers, cut to size, could be dropped when it was desired to close the face. In later shields used for the construction of tube railways in London the tendency has been to enlarge the opening and make it circular in shape, so that the diaphragm extends hardly at all inside the circular stiffening ring. The large opening helps the work of excavation, particularly with rotary excavators which have been used greatly during recent years.

30. Diaphragm in Small Shields in Waterbearing Ground.—As previously stated, for small shields in waterbearing ground the diaphragm may be divided into two parts so as to form a water trap. The upper part is placed immediately behind the cutting edge and the lower part should be far enough behind the upper to allow for convenient access through the trap to the face. Generally the clear width of the opening should not be less than 3 ft. To insure the working of the water trap the bottom edge of the upper diaphragm should reach not less than 6 in. below the upper edge of the lower diaphragm. This will permit some rolling of the shield without destroying the efficacy of the trap.

31. Diaphragms in Large Shields.—In large shields for use in dry ground the diaphragm scarcely exists. In shields for waterbearing ground, part of the opening in the pockets is closed by means of diaphragms. The remaining part should be provided with some means of closing the shield completely. The location of the diaphragm and the construction of the doors is determined partly by the size of the working chamber desired and partly by the kind of door used.

32. Length of Shield.—The length of the shield is the sum of the lengths of the cutting edge, the internal structure and the tail. The smaller the ratio of the length to the diameter, the easier the shield is to steer. Previous experience indicates that while a greater proportion may be used, it is preferable to keep it below 0.75. Table X shows the relation between length and diameter of various shields which have been used in the construction of tunnels.

33. Shield Doors.—The reason for applying doors to close the openings in the diaphragm are, first, to secure the face and the tunnel during temporary closing down of the work, and second, to prevent the water and ground from entering the tunnel in case of a blow.

34. Doors for Small Tunnels.—For shields in dry, firm ground the method of closing the opening by means of planks as described in par. **29**, is satisfactory, when no necessity for a hurried closing is anticipated. In small shields in waterbearing ground, provided with a water trap, the tunnel is protected against an inrush of water and ground as long as the air pressure is high enough. For additional security the opening in the trap should be provided with a hinged cover that may be closed when occasion demands.

35. Doors for Large Shields in Firm Waterbearing Ground.—A completely satisfactory door construction for a large shield in firm waterbearing ground as yet has not been devised. The problem is to provide a door which can be closed tightly, in the case of a blow or a run of ground, without being jammed by the inflowing ground, but which on the other hand will provide reasonably convenient access to the face. For this reason, as a rule, no attempt is made to provide means for quickly closing the openings in the shield, reliance being placed on careful work in the face. Doors are provided, however, for the purpose of protecting the tunnel when work is suspended for any reason.

TABLE X.—RELATION OF LENGTH AND DIAMETER OF TUNNEL SHIELDS

Ref. No.	Tunnel	Length of shield, feet	Diameter of shield, feet	Ratio of length to diameter
(A-36)	West Water Street	9.00	7.00	1.29
(S-44)	Dee Sewer	6.81	8.71	0.78
(A-1)	Mystic River	4.50	9.00	0.50
(C-1)	Mersey	11.58	10.25	1.13
(A-8)	Havana Sewer	7.96	10.58	0.75
(E-4)	Ravenswood	7.20	11.06	0.65
(G-8)	Kiel Canal	11.12	11.33	0.98
(E-10)	City & South London	6.50	11.42	0.57
(A-26)	Cleveland New Intake	15.08	12.13	1.24
(S-2)	Glasgow District	6.42	12.20	0.53
(E-13	Lea	11.50	12.31	0.94
(E-9)	Central London	7.04	12.67	0.56
(E-11)	Greenwich	13.58	13.00	1.04
(E-15)	Baker Sreet and Waterloo	9.71	13.00	0.75
(A-22)	Gowanus	15.00	14.87	1.01
(A-16)	Battery	9.50	16.98	0.56
(A-21)	Steinway	11.75	17.25	0.68
(S-1)	Glasgow Harbor	8.50	17.25	0.49
(A-27)	Old Slip	16.33	18.04	0.91
(A-30)	14th Street	15.31	18.46	0.83
(A-28)	Whitehall	16.33	18.50	0.88
(A-35)	60th Street	16.06	18.57	0.87
(A-33)	Gayoso Avenue	9.00	19.83	0.45
(A-6)	Hudson	10.50	19.92	0.53
(A-23)	Lawrence Avenue	11.33	20.16	0.56
(A-5)	Sarnia	15.25	21.50	0.71
(A-18)	P. R. R. Hudson River	15.92	23.52	0.68
(A-19)	P. R. R. East River	18.00	23.54	0.77
(A-34)	Dorchester	12.50	24.37	0.52
(F-12)	Concorde Metropolitain	14.96	26.08	0.58
(E-7)	Blackwall	19.50	27.67	0.71
(E-17)	Rotherhithe	18.00	30.67	0.59
(G-10)	Elm	14.00	35.58	0.39

For this purpose the doors may be of the swinging type hinged at the top or sides; of the sliding type, moving either horizontally or vertically or the stop-log type, wherein pieces of timber or metal are dropped into housings or grooves along the edges of the openings. The difficulty with all emergency gates is that, in the emergency a piece of wood or stone is most apt to get caught between the door and the frame thus defeating the object

sought. This suggests, for use in bad ground, a double series of doors, one set at the front of the internal structure and the other at the rear end. The front set of doors would be closed first and if not tight, the second set could be brought into operation under the partial protection of the front set.

36. Air Locks in Shields.—In the original designs for the shields for the Blackwall tunnel (E-7) and for the Pennsylvania tunnels under the East River (A-19) the access to the face was provided through air locks with the usual set of double doors. The shield for the Spree tunnel (G-1) was provided with a similar air lock. The purpose was to make it possible to use a higher pressure in part or all of the face than in the tunnel. These air locks were not used, and in practice such devices would not appear workable. A blow at the face would quickly exhaust the air in the shield. As for keeping different air pressures at different levels of the shield, when working in open ground, the air in the higher pressure chamber would soon escape through the ground into the lower pressure chamber and make the maintenance of different air pressures impossible.

37. Gate Valves for Soft Ground.—In soft, flowing silt it is customary to displace bodily as much as possible of the ground by driving the shield "blind," or with all the openings in the face of the shield closed. Usually, however, the proper guiding of the shield necessitates some of the ground to be taken into the tunnel. It is somewhat difficult to regulate the flow satisfactorily through the partly open shield doors, and it is probable that a better method would be to provide large gate valves in the diaphragm of the shield, through which the flow could be regulated more readily.

C. SHIELD APPLIANCES

38. Shield Jacks.—During the construction of a shield driven tunnel, when the erection of a ring of the tunnel lining has been completed and the excavation for the next ring width has been carried out, the shield is advanced that distance so that the erection of another ring may proceed. The shoving, or moving forward, of the shield is accomplished by means of hydraulic jacks attached to the shield structure and reacting against the tunnel lining previously erected.

39. Resistances to Motion.—In order to move the shield forward the following resistances must be overcome: (*a*) the friction of the ground on the exterior surface of the shield, (*b*) the friction of the lining in the tail of the shield, and (*c*) the resistance to displacement of the ground in front of the shield which has not been removed by previous excavation.

40. Magnitude of Resistances.—If the ground in front of the shield were excavated completely before the shield advanced, the frictional resistances would determine the required jack pressures. The frictional resistances, however, usually form only a small item. While the excavation may be removed completely for a certain length of the tunnel, as for example where it is driven through rock, this will be done rarely if ever, throughout the full length of the tunnel, because even if it were possible to carry out the complete excavation it would be more economical to make the shield do part or all of the work of excavation. In small shields, driven through clay, only the middle part of the face is excavated by hand. Short wooden stakes, or piles, supported against the shield are used for breaking down the remainder by forcing the shield forward under the pressure of the shield jacks. In the shields used in the same kind of ground and equipped with mechanical excavators the shield jacks are used to feed the shield forward and to break down the portion of the ground around the circumference not removed by the excavator. In Hudson River silt no excavation is carried out in front of the shield by hand. In small tunnels the shield is shoved blind and in larger tunnels part of the displaced material is taken in through the partly open shield doors. In large tunnels driven through waterbearing ground it is seldom possible or convenient to carry an air pressure high enough to keep the bottom dry, so that it can be excavated by hand, and this part of the ground is then displaced by the shield as it is pushed forward. Owing to these conditions it is not possible to give any definite rules as to the power the shield jacks should be able to develop, except that the greater the potential power of the shield jacks the better are the chances of overcoming obstacles met during the driving.

41. Jack Pressures of Shields of Existing Tunnels.—Table XI gives particulars of jack pressures provided for driving the shields used for the construction of existing tunnels.

TABLE XI.—PRESSURES OF SHIELD JACKS

Ref. No.	Tunnel	Ext. diameter of shield, feet	Hydraulic jacks		Hydraulic pressure		
			No.	Diameter, inches	Pounds, per sq. in.	Total tons	Per sq. ft. of shield, pounds
(S-4)	Dee Sewer	8.71	6	6½	2,240	225	7,500
(E-4)	Mersey	10.25	10	7	4,000	770	18,700
(C-1)	Havana Sewer	10.58	8	5	5,000	397	9,000
(A-8)	Ravenswood	11.06	12	5	5,000	595	12,400
(G-8)	Kiel Canal	11.33	10	.....	.....	600	12,000
(A-26)	Cleveland New Intake	12.13	12	9	3,000	1,135	19,800
(S-2)	Glasgow District	12.20	6	6½	1,000	100	1,700
(E-91)	Central London	12.67	6	7	1,600	185	2,900
(E-15)	Greenwich	13.00	13	7	3,400	850	12,800
(E-12)	Bakerloo	13.00	14	6	2,400	475	7,200
(A-26)	Gowanus	14.87	14	8½	3,500	1,400	16,100
(A-1)	Battery	16.98	14	8	5,000	1,750	15,500
(S-1)	Glasgow Harbor	17.25	13	7	1,000	250	2,100
(A-27)	Old Slip	18.04	17	8	5,000	2,125	16,700
(A-30)	14th Street	18.46	17	8	5,000	2,125	15,900
(A-28)	Whitehall	18.50	17	8	5,000	2,125	15,800
(A-35)	60th Street	18.57	20	8	5,000	2,500	18,400
(A-33)	Gayoso Avenue	19.83	16	7½	5,000	1,760	10,400
(A-6)	Hudson	19.92	16	8	4,000	1,600	11,400
(A-23)	Lawrence Avenue	20.16	24	5¾	3,500	1,100	6,900
(A-5)	Sarnia	21.50	24	8	3,000	1,800	10,000
(A-18)	P. R. R. Hudson R.	23.52	24	8½	5,000	3,300	15,200
(A-19)	P. R. R. East R.	23.54	27	9	5,000	3,850	17,500
(A-34)	Dorchester	24.37	24	8	5,000	3,000	12,900
(F-12)	Concorde Met.	26.08	27	8½	5,000	3,830	14,300
(E-7)	Blackwall	27.67	{28 6	8} 10}	6,100	5,785	19,200
(E-17)	Rotherhithe	30.67	40	9	6,000	6,700	18,100
(G-10)	Elm	35.58	20	.....	.....	.....	11,800

NOTE.—In this book a ton means a weight of 2,000 lb.

42. Working Pressures.—It will be seen from this table that the maximum hydraulic pressure has ranged around 5,000 lb. per square inch. The usual working pressure, however, is not as high as this, which is used only in special cases. The working pressure is generally about 3,500 lb. per square inch.

43. Location of Jacks.—The jacks are placed in the shield in such a manner that their cylinders move forward with the shield

while the piston rods or plungers remain stationary during the shove, pressing against some immovable object, generally the tunnel lining. In order to bear against the lining the jacks are placed circumferentially as close to the skin as possible. Usually

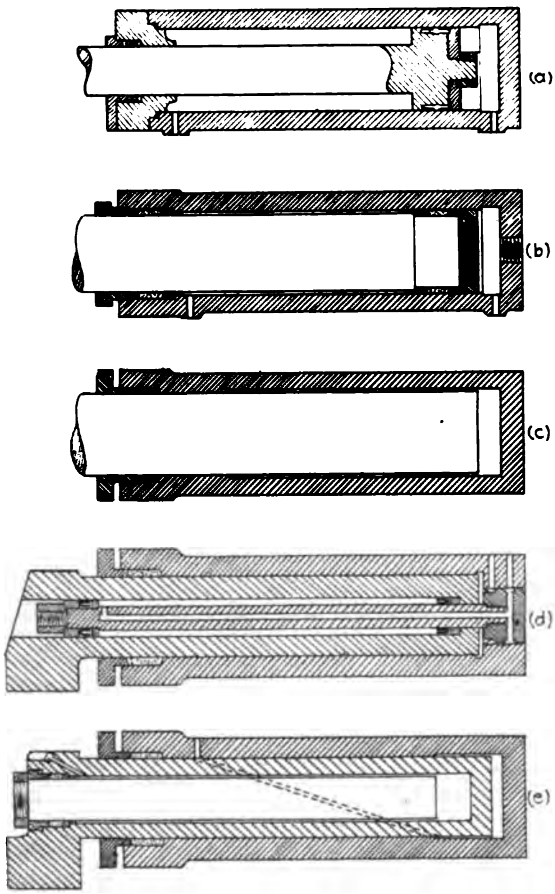
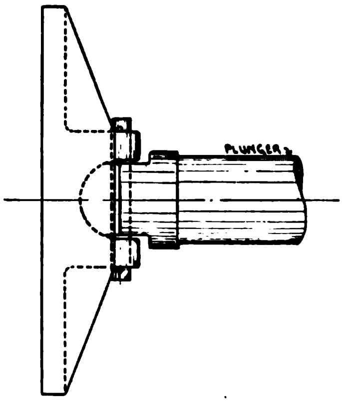


FIG. 67.—Types of shield jacks. (*a*) and (*b*) piston type, (*c*) single acting type, (*d*) and (*e*) single acting with auxiliary plunger.

the jacks are spaced uniformly around the circumference, but in some cases more jacks have been placed below the horizontal diameter than above, because greater force is generally needed at the bottom than at the top, owing to the tendency of the shield to "dive."

44. Types of Jacks.—When the shield has been shoved forward a ring width the plungers of the jacks must be pulled back to make room for the erection of the lining. In order not to waste time and labor in doing this the jacks preferably should have some mechanical means for pulling back the plungers. For this reason the piston type of jack has been used frequently, particularly in small diameter shields. Figure 67 shows two forms of jacks of the piston type (*a* and *b*), used for shield jacks. This type has the disadvantage, however, that when the packing of the piston has to be adjusted, the whole jack must be taken apart. For this reason a single acting type as shown in Fig. 67, (*c*) has been used in some cases. In this type the packing is readily adjusted from the outside, but the plunger must be pushed back by hand, and owing to the large volume of water to be emptied through a small outlet, this is a slow process. These conditions have led to the development of a single acting type with auxiliary plunger to push back the main plunger. Figure 67 (*d* and *e*) show two designs of this type. In the first design the plunger forms the cylinder for a smaller piston, the rod of which passes through the bottom of the main plunger and is fastened to the bottom of the main cylinder. The water connection for both the main and secondary cylinders are at the bottom of the main cylinder as shown. In the second design the pull-back is a secondary plunger inserted from the front in the main plunger. In the forward push the inner plunger moves with the main plunger, but in pulling back, the inner plunger reacts against the tunnel lining and forces the main plunger back into its cylinder. The secondary plunger is then pushed back by hand. On account of its small diameter this is done readily.



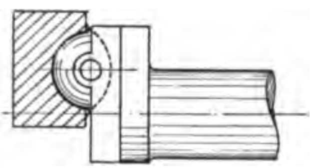


FIG. 68.—Shield jack equipped with ball and socket joint.

45. Heads of Jacks.—The head of the jack plunger should be made of such a shape that the thrust is distributed over as large an area as possible of the tunnel lining. In cast iron lined tunnels it is often necessary to make the head eccentric to carry the thrust on line with the skin of the lining. This subjects the plunger or piston rod to a bending stress which should be taken into account in the determination of the diameter of the plunger. When the axis of the shield forms an angle with that of the lining the jack heads will not bear squarely against the lining, and this may cause breakage of the lining. In order to avoid this, in some cases the head has been made with a ball-and-socket joint as shown in Fig. 68.

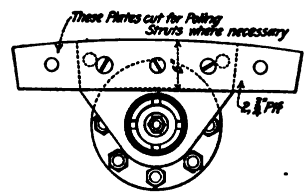


FIG. 69.—"Grouting strip" attached to head of ram. (From *Eng. News*, Dec. 13, 1906.)

46. Grouting Strips.—Usually the heads of the plungers are equipped with grouting strips or flat plates as shown in Fig. 69. When all the jacks are extended these form a complete ring closing the space between the lining and the shield. The purpose of this ring is to prevent the grout, ejected outside of the lining to fill the space left by the tail of the shield, from flowing out.

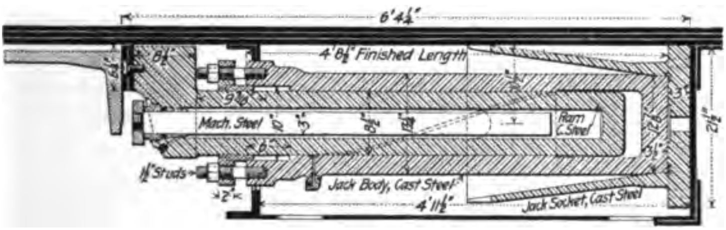


FIG. 70.—The housing of a shield jack. Pennsylvania Railroad Hudson River Tunnels (A-18). (From *Eng. News*, Dec. 13, 1906.)

47. Jack Housing.—In shields with a cast iron stiffening ring as described in par. **20** and **21**, the jack cylinders are cast with a flange as shown in Fig. 66, so that they may be bolted to the shield structure. In shields with an annular box-girder construction the jacks are inserted from the rear of the box-girder, and to facilitate their proper placing a steel casting is provided in each compartment furnished with a flaring socket, as shown in Fig. 70 which guides the jack to its proper seat. At the rear the cylinder

is supported on the annular web plate of the box-girder and is held in place by plates cut to shape and fastened to the web-plate by means of stud bolts.

48. Piping for Shield Jacks.—The piping for the shield jacks involves usually two connections to each jack, one for the supply to the main cylinder and one for the pull-back. If any of the

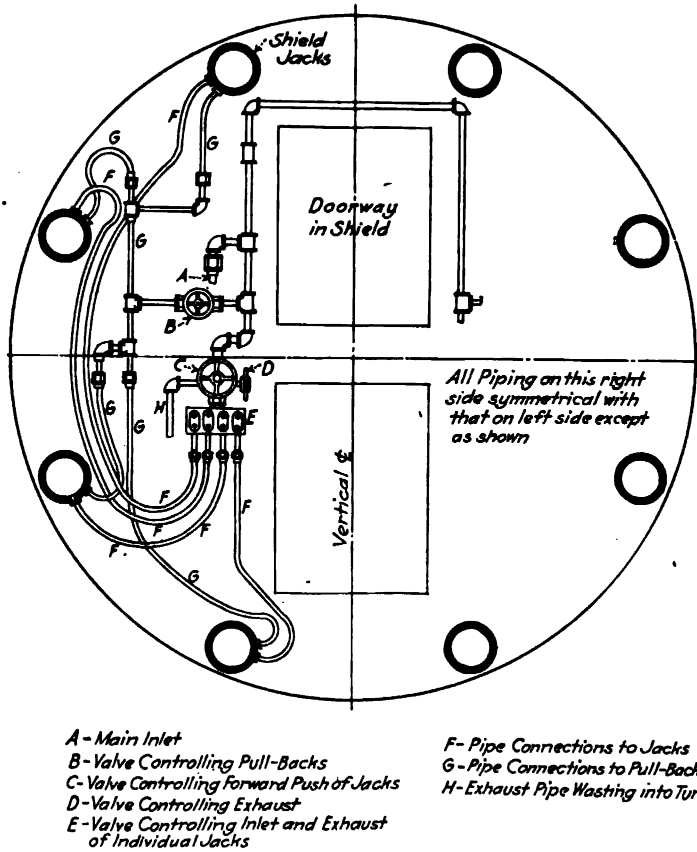


FIG. 71.—Diagram of hydraulic piping and valves on a shield.

connections are at the forward end of the cylinder, either hand holes should be provided in the inner skin to permit the connection being made, as shown in Fig. 70, or the socket and the opening in the rear web plate should be large enough to permit the cylinder with the connections made to be inserted from the rear. The pipe used is generally heavy copper. The controlling

valves are arranged so that the jacks may be operated singly or in groups. The piping should be attached to the shield in such a manner that it neither obstructs the openings nor is exposed to damage. The controlling valves should be placed so that they can be manipulated easily.

49. Example of Piping.—Figure 71 shows diagrammatically the arrangement of the piping for a shield with 8 jacks. The water is received through a detachable copper pipe at *A* and the pipe line is immediately divided into two branches, one for the left and one for the right side of the shield. The latter branch is carried across the top of the opening in the shield and is then arranged symmetrically with that on the left side. The left side branch runs downward and is divided into two lines, one for the pull-backs, controlled through the valve *B*, and another for the forward push, controlled through the valve *C*. Below this valve is a valve-box *E*, with individual valves through which the water is distributed by the pipes *F* to each of the four jacks on the left side of the shield. The valve-box also contains four valves for the exhaust water, which passes through the main exhaust valve *D* and is wasted into the tunnel through the pipe *H*. The water for the pull-backs, after passing through the valve *B* is distributed by the pipes *G* to the four jacks.

50. Segment Erector.—In small shields the erection of the lining segments is done by hand, but when the size is large enough to have one or two more working platforms in the shield, the erection is generally done by mechanical power, and the implement used for this purpose is called an erector. The erector consists essentially of an arm which swings on a horizontal shaft parallel to the longitudinal axis of the tunnel and which may be shortened or lengthened as desired.

51. Location of Erector.—The erector may be carried on a separate stage behind the shield, as shown in Fig. 72, but in most tunnels it is mounted on the shield. The principal advantage of the latter arrangement is that the erector is moved forward with the shield and no adjustment is required to bring it into proper position for erecting the lining. On the other hand, if the erector is mounted on a separate stage, the proper adjustment is made more readily, when the lead is great, without straining the erector arm and when out of repair the erector may be removed without interfering with the work at the shield. When mounted on the shield the turning axis of the erector usually coincides with that

Fig. 72.—A tunnel shield with erector carried on a separate stage. Hudson and Manhattan Railroad (A-17). (Courtesy of *Hudson and Manhattan Railroad.*)

of the shield, but in a few instances two erectors have been mounted symmetrically on the shield, each with its turning axis on the horizontal diameter of the shield. The purpose of using two erectors has been to speed the work of erection, but it is doubtful if the efficiency is increased. With two erectors the arm of each should be able to reach rather more than one-half the circumference of the lining. With one erector the arm must be able to make a complete revolution.

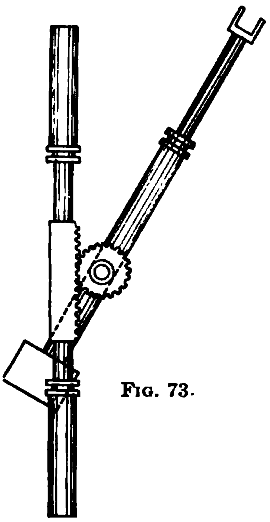


FIG. 73.

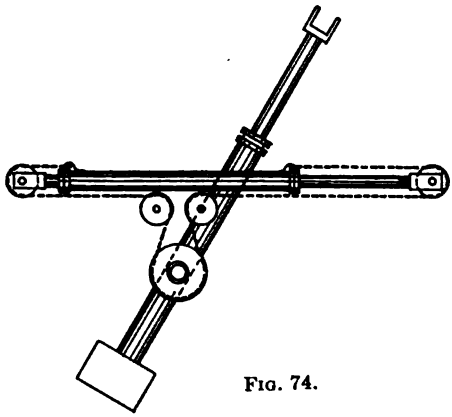


FIG. 74.

FIG. 73.—An erector turned by rack and pinion. Turning jacks vertical.
FIG. 74.—An erector turned by pulleys and chains. Turning jacks horizontal.

52. Turning Mechanism of Erector.—The erector is mounted on a horizontal shaft around which it turns. The turning is accomplished by means of two single acting hydraulic jacks through a rack and pinion or by pulley and chains. The turning jacks should be placed so that they do not obstruct the openings in the shield. Usually they are placed, therefore, on line with the platforms or partititions of the shield. Figure 73 shows diagrammatically the arrangement of an erector turned by rack and pinion with the turning jacks placed vertically and Fig. 74 shows the same of an erector turned by pulleys and chains and having the turning jacks placed horizontally.

53. Erector Arm.—The erector arm is that part of the erector which moves in a plane perpendicular to the axis of the shield and to which the segment of the lining is attached for erection.

The arm should be placed so that the plane in which it turns is one-half of a ring width from the leading end of the last ring erected, when the shield has been moved forward a ring width. The arm, when extended, should be able to reach nearly to the outside of the lining and when drawn in there should be ample room for manipulating the lining segments and for attaching them to the erector arm. The erector arm consists of a double acting hydraulic jack and a stiff beam or frame which has a sliding support on the jack cylinder or on special castings attached to the central shaft and which is connected with the head of the plunger so that it moves in and out with the plunger. This arrangement relieves the plunger of the bending stress due to the weight of the segment carried by the erector. A counterweight is usually provided on the erector arm at the end opposite to the head, in order to decrease the turning moment.

54. Erector Grip.—The end of the erector arm which carries the segment of the lining is furnished with a grip, by means of which the segment is attached to the arm. For cast iron linings the equipment for attachment also includes usually a bar which is inserted in the bolt holes in the segment to be lifted and to which the erector grip is attached. The bar is usually turned to a smaller diameter at the ends so that it will enter the bolt holes and is provided with a sleeve or catch to prevent it dropping out while being used. The erector head is furnished with one or two plates with slotted holes fitting around the bar, or the bar may have a plate attached and the connection is then made by means of a bolt through the plates on the bar and on the erector head. The essential points about the erector grip are that the attachment should be easy and that the segment should be held squarely against the outer circumference of the tunnel so that the adjustment by hand may be slight. There should also be some side play so that the segment may be placed in its proper position when the shield has a lead on the lining and the erector head should be able to push with the full force of the jack against the segment. When the segments are heavy it may be advisable to use two bars instead of one.

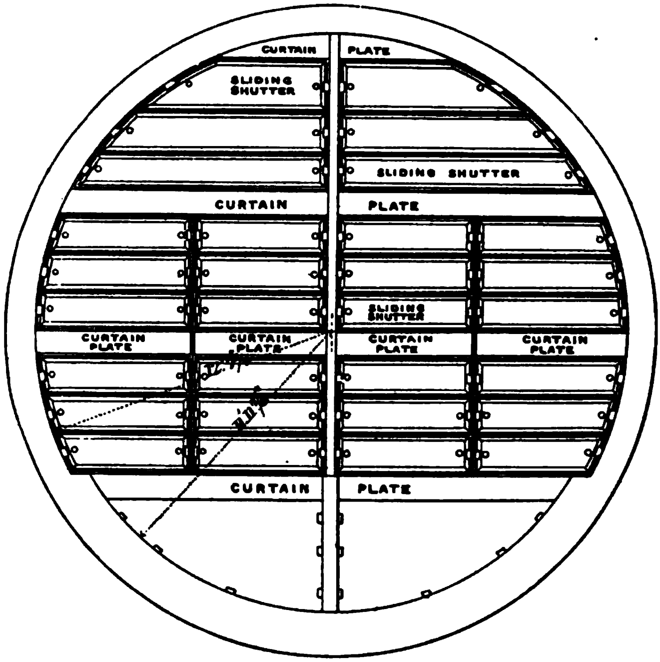
55. Face Supports.—As long as the shield is stationary the poling of the face may be supported against the shield, but before the shield is shoved forward this support must be replaced with some that is independent of the movement of the shield. In some cases the face has been supported by struts extending

through the working openings in the shield and bearing against cross timbers supported by the lining, but this method cannot be called a good one, because it interferes with the work and prevents a hurried closing of the opening. An improvement on this is to carry the struts through specially provided openings, furnished with sleeves that insure reasonable tightness. See Fig. 64. In other cases the face has been held by telescopic struts, called "guns," supported against the shield in front of the diaphragm. These struts are usually made of two pipes sliding inside each other and held in place by the friction of a set screw. As the shield advances the friction is overcome and the pipes telescope while continuing contact with the face.

56. Face Jacks.—The most satisfactory method of supporting the face while the shield advances is by means of face jacks, which are usually single acting hydraulic jacks, placed horizontally parallel to the axis of the shield and which can be extended forward to contact with the face. During the forward movement of the shield the hydraulic pressure on the face jacks is retained, but the greater force of the shield jacks forces them to close up, driving the water in the jacks back into the system. By this means a constant and uniform pressure is maintained for the support of the face. The jacks, when extended, should reach beyond the front of the cutting edge and the stroke should be equal to the width of a ring of the lining. The face jacks are usually placed below the shield platforms. In some shields the cylinders of the jacks are fixed to the structure and the plungers extend to support the face. In others the plunger is fixed and the cylinder is extended. The latter method is perhaps the better, because it protects the plunger against dirt and damage, and it is particularly suitable when the jacks also are used for the support of a sliding extension of the platforms of the shield. See Fig. 63.

57. Sliding Platforms.—The purpose of the sliding platforms is to provide working platforms extending close up against the face of the excavation and to provide protection for the men working at the lower levels. The sliding platform consists of a steel plate laid on top of the shield platform and attached at its front end to the forward end of the face jacks. The cylinder of the jacks, which moves forward, runs in guides capable of supporting the load on the extension platform cantilevering over the fixed platform.

58. Supporting Shutters.—The face supports so far described do not take the place of face poling, but only hold it in place. In some instances, notably on the Blackwall tunnel shield, an attempt has been made to replace the poling by means of movable

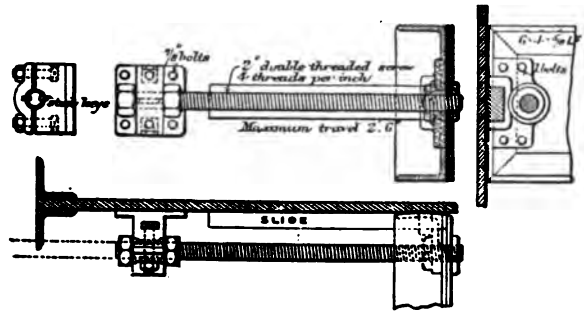


Scale, ¼ inch = 1 foot.

FIG. 75.—Blackwall tunnel (E-7) shield. Face shutters. (From *Proc. Inst. C. E.*, vol. 130.)

shutters attached to the shield. In that shield the pockets, except at the bottom level, were furnished with shutters built up of plates and angles as shown in Fig. 75. The vertical depth of these shutters was about 18 in. and they extended for nearly the full width of each pocket. At both ends each shutter was held in place by means of a 2-in. diameter screw, threaded the full length (Fig. 76). At the rear end each screw passed through a hole in a bracket attached to the partition wall of the pocket and was held in place by means of a nut at each side of the bracket. The ends of the shutters traveled on slides, also attached to the partitions. Immediately after the shield had been moved forward the shutters would be in a position close to the supporting brackets. The top shutter in each compartment

would then be moved a few inches forward or backward so that the ground in front of it could be removed. This process would be repeated until all the shutters were fully extended. When the shield was then pushed forward, the nuts on the screws were gradually turned in such a manner that contact was always maintained with the ground. As, however, the area of the



Scale, ¼ inch = 1 foot.

FIG. 76.—Blackwall tunnel (E-7) shield. Mechanism of face shutters. (From *Proc. Inst. C. E.*, vol. 130.)

shutters was only about 60 per cent of the corresponding shield area, the remaining 40 per cent of the ground had to be displaced by the shield and taken in at the shutters, which meant that the shutters had to travel about twice as far back in relation to the shield as the shield moved forward. When the ground would not permit the shutters being started, a small hand hole provided in each shutter would be opened and the ground scraped out in front until the shutter could be moved. The shutters worked fairly well on this shield, which was driven through waterbearing gravel. Similar shutters were applied to later shields, but without success, and the shutters were removed. Probably the nature of the ground was different. The principle of the shutters is not entirely satisfactory, because of the necessity of displacing bodily a large part of the ground in front of the shield.

59. Mechanical Excavators.—Although shield tunneling is a continuous repetition of a sequence of operations, each ring length constructed has its own problems. In the matter of excavation the character of the ground may change from place to place in such a manner that only hand labor is flexible enough to cope with the varying conditions. Mechanical means of excavation are most efficient where the ground is uniform in character.

60. Thomson's Excavator.—One of the first mechanical excavators employed was invented by T. Thomson and used in 1897 on the construction of the Central London Railway (E-9) in London clay. This machine was independent of the shield. The shield, which had an outside diameter of 12 ft. 8 in. and was of the type described in par. **20** and **29,** had a large opening in the diaphragm so as to make room for the mechanical excavator. The excavator was mounted on a carriage and consisted essentially of a bucket conveyor supported on a movable arm and operated by an electric motor. The excavation was carried out by setting the carriage so that the bucket at the end of the arm was in contact with the face. As the buckets dug out the ground the arm was raised until a cut had been made of the width of the buckets and of the full height of the tunnel. The arm was then moved sidewise and the process repeated until the excavation had been completed for a length equal to the length of a ring of the tunnel lining. The carriage was then run back from the face to make room for the erection of the lining. In small tunnels a machine of this type may be constructed to carry out the work efficiently if the ground is suitable, but it will occupy almost all the space available behind the shield. In larger tunnels it is not probable that the machine could be used, because the face must be standing without support and the shield can have no internal bracing.

61. Price's Excavator.—Another type of mechanical excavator, invented by John Price, combines the excavator with the shield. This machine also was used first in 1897 for excavation in London clay and since then has been used successfully in the construction of a number of tunnels in London. The shield (Fig. 77) is in general of the same type as other small diameter shields used in London clay, but it is provided with a central shaft A, on which is mounted the excavator in front at the cutting edge. The excavator has 6 radial arms B, to which are fastened cutting knives C, extending in front of the arms. The knives are placed at different distances from the center on each arm, and when the arms revolve they cut concentric grooves in the face from 4 to 5 in. apart, resulting in a complete break-down of the face to the depth of the cut. The central part of the arms is not provided with knives, but carries instead a triangular plate D, provided with teeth which break down the ground as the shaft revolves. The excavator is revolved by means of a series of

gears. On the back of the arms is attached a large gear wheel E, with the teeth on the inside of the rim. This wheel is turned by the pinion F, which is driven by the three sets of gears, G-H, I-K and L-M. The motive power is furnished by an electric motor N, mounted on the same shaft as the gear wheel M. Each of the radial arms carries a bucket O, which scoops up the

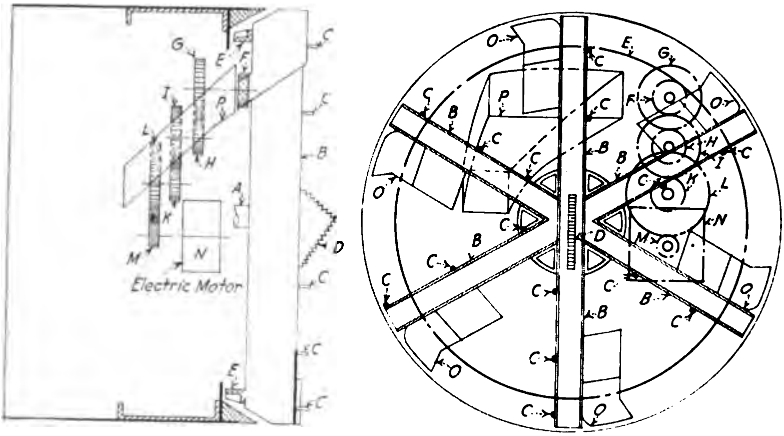


Fig. 77.—The John Price rotary excavator applied to a small shield for work in clay.

earth broken down by the knives and empties it into a chute P at the top of the shield. The earth falls onto a conveying belt, mounted on a carriage behind the shield and is finally dumped into the mucking cars. In the beginning some difficulty was experienced in steering the shield with the excavator attachment, but this was overcome as experience was gained and the machine has been found efficient. It has been used, not only in London clay, but also, in the construction of the pilot tunnel for the Rotherhithe tunnel, for driving through varying ground, including waterbearing gravel and soft rock. Figure 78 is a photograph of the front and back of this machine.

62. Carpenter's Excavators.—In the construction of the Detroit sewer system a mechanical excavator, originally devised by Charles Bonnet, was used. The first type, known as the Carpenter machine, was used in 1914. This machine was mounted on a carriage and consisted of a horizontal shaft carrying on its end a plough-shaped boring knife and an arm placed perpendicular to the shaft. This arm formed the guide for a cutting tool which by means of a rack would move automatically from one

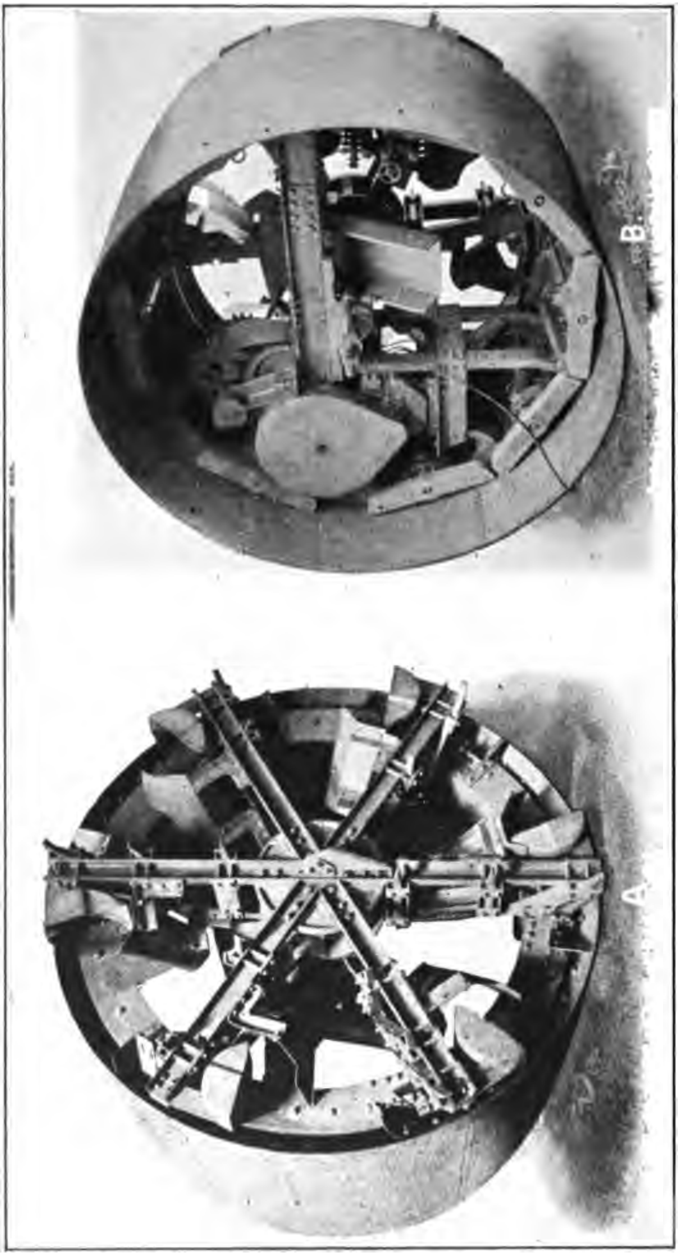


Fig. 78.—The John Price rotary cutter in a small shield to work in London clay. (A) Front view. (B) Rear view. (From *Trans. Am. Soc. C. E.*, vol. 54, Part F.)

end of the arm to the other as the shaft revolved. The shaft with the boring knife and the arm was revolved by an electric motor, mounted on the carriage. In employing the excavator the shaft is centered on the axis of the tunnel and the motor started. The shaft with the knife, but not with the cutting tool, is first geared in and the knife cuts a conical hole, about 15 in. deep, which is equal to the length of one ring of the tunnel lining. The boring knife is then stopped and the arm set in motion, but the knife remains in position to steady the machine. The cutting tool, mounted on the arm, is 6 in. deep and cuts the ground to this depth, making a spiral cut starting at the central hole already made, and continues to revolve until the whole face has been excavated to a depth of 6 in. The process is then repeated until a full ring width has been excavated. The excavated material falls to the bottom of the tunnel and is picked up by hand and placed on a conveyor belt which removes it to the mucking cars.

63. Anderson's Excavator.—In a more recent design of this machine, called the Anderson Excavator, the cutting knife is made to cut a thin sheet of earth the full diameter of the face at each revolution of the shaft, and the shaft is fed forward as the cutting progresses, until a length equal to the width of a ring of the tunnel lining has been excavated. In this design radial buckets have been provided which carry the excavated material to an axial screw which feeds it onto a belt conveyor leading to the muck cars.

64. Limitation of Use.—The Carpenter and Anderson machines were used in Detroit without a shield. This is only possible when the ground is of such a character that it will stand without support until the lining is erected. The machine is from 9 to 12 ft. long and this length of tunnel must be left unsupported.

65. Anderson's Excavator with Shield.—In conjunction with a shield this type of excavator was used for a time for driving a tunnel for the Cleveland West Side water supply (A-26) in 1915, but was discarded before the tunnel was completed. It is stated, (*Eng. News*, Jan. 18, 1917) that the immediate reason given was a change in the nature of the ground, but that subsequent experience showed that hand excavation gave nearly as rapid progress with the same number of men, was free from liability to interruption, avoided the use of electric motors at the face and saved the operating cost of the machine.

D. SPECIAL TYPES OF SHIELDS

66. Roof Shields.—While the roof shield in broad principles resembles the usual tunnel shield, it is a modification of this in so far that it covers only the upper part of the tunnel. The lower part of the tunnel is constructed by other means, generally by ordinary mining operations. The roof shield, therefore, is suitable only in such ground as where this is practicable. The original roof shield was conceived probably as a means of driving

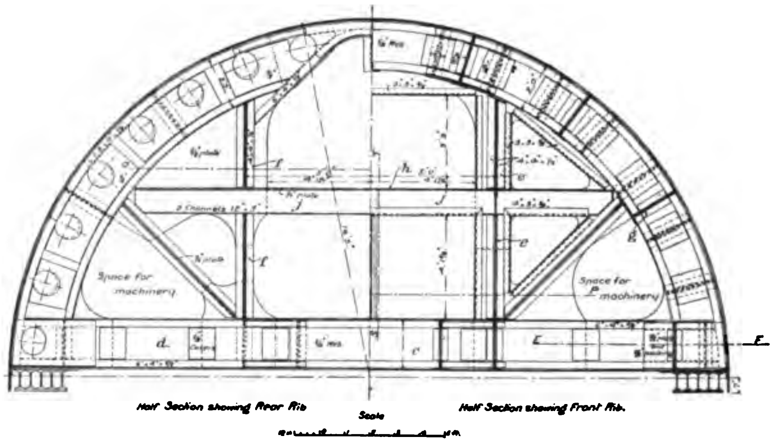


FIG. 79.—East Boston tunnel (A-13). Roof shield. Cross section front and rear. (Courtesy of *W. C. Copperthwaite.*

a tunnel with a shallow cover, where it was not permitted to disturb the surface during the construction, but it has been found useful also for the construction of deeply overlaid concrete lined tunnels. As stated in Chap. VIII, the pressure of the shield jacks makes difficult the use of concrete for the primary lining of a shield driven tunnel. When a roof shield is used, the invert and the sidewalls may be built without being subjected to the thrust of the jacks, and as regards the arch of the tunnel, by various devices as described in Chap. VIII, it has been found possible to place the concrete without being damaged by the pressure of the shield jacks, which is usually less intense than for ordinary shields.

67. Construction of Roof Shield.—As in the usual tunnel shield the roof shield consists essentially of a skin, covering the arch of the excavation and braced by an internal structure. Forward, the skin forms a hood under which the work of excavation is carried out, and the rear portion of the skin forms a tail

under cover of which the lining is erected. The shield is pushed forward by means of hydraulic jacks and is usually supported on rollers running on a track laid ahead of the shield.

68. Example of Roof Shield.—Figures 79 and 80 show as an example the roof shield used in the construction of the East Boston tunnel in 1899 (A-13). This shield was semi-circular in shape and had an external radius of 14 ft. 5 in. The overall length was 13

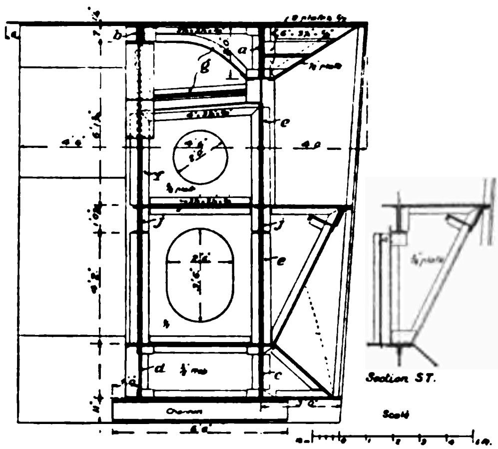


FIG. 80.—East Boston tunnel (A-13) roof shield. Longitudinal section. (Courtesy of *W. C. Copperthwaite.*)

ft. 6 in. and the bottom bearing was 6 ft. 6 in. long. The skin was made of two thicknesses of 5/8-in. plate and was braced by two semicircular trusses and longitudinal girders of the same depth as the trusses. Two working platforms were provided, one at the level of the top of the bottom chord of the trusses and one at about half the height of the shield. The shield was propelled by 16 hydraulic jacks with a capacity of 75 tons each. The bearing for the shield consisted of a series of rollers with a diameter of 8 in. and with a length of 16 in., running on a track laid on top of the side walls previously constructed.

69. Non-circular Shields.—Excepting roof shields, most shields have been made circular. There are, however, some instances where they have had other shapes. The Brunel shield, used for the construction of the Thames tunnel, (E-1) was rectangular in cross-section. Its width was 37 ft. 6 in. and its height 22 ft. 3 in. An elliptical shield was used for the construction of the Collecteur de Clichy Intra Muros (F-4) forming

part of the sewer system of Paris. The vertical diameter of this shield was 19 ft. 5 in. and its horizontal diameter was 23 ft. 10½ in. The largest shield driven tunnel so far built, the Elm tunnel (G-10) on the Frankfurt-Berlin Railroad in Germany, was driven by means of a shield having a horseshoe shaped cross-section. The width of this shield was 37½ ft. and the height was 35½ ft. Besides this tunnel, several tunnels driven by shield in Germany have cross-sections other than circular. Rectangular shields were used in Baltimore (A-7), for driving bottom headings in connection with the first roof shield.

70. Spree Tunnel Shield.—In the construction of a tunnel under the River Spree at Berlin in 1896–1899 (G-1) a shield was used which has some interesting features. Figure 65 shows diagrammatically a longitudinal section of this shield. The ground through which the tunnel was driven was fine water-bearing sand, which flowed under normal air pressure, but which would stand on a slope when dried by compressed air. The diameter of the tunnel was 13 ft. 1½ in. The shield was 26 ft. 7 in. long at the top and overhung the bottom 11 ft. 10 in., the purpose being to make the front plane of the shield coincide with the natural slope of the dried sand. The sloping front was covered with a diaphragm in which were openings provided with doors. Behind the sloping diaphragm was another but vertical diaphragm provided with an air lock near the center, through which access to the face was obtained. An emergency exit was placed above the air lock. The method of working was to open, one at a time, the doors in the sloping diaphragm and excavate in front of the opening. When sufficient material had been excavated the shield was shoved forward.

71. Differential Pressure Shields.—The external pressure on the face of a tunnel excavation increases from the top to the bottom. In small tunnels the difference between the top and bottom pressures is not so great but that the uniform pressure of the compressed air may support it, but when the diameter of the tunnel is large, it is difficult to balance properly the external pressures. This has led to the consideration of shields designed to maintain different air pressures at different levels of the shield. The shields of the Blackwall and the Pennsylvania Railroad East River tunnels, previously mentioned, were of this class, but no use was made of the device for obtaining differential pressures. So far as we know, no shield has been used in which a differential

pressure has been maintained between upper and lower floor levels. In fact, it is difficult to see how this could be done in open ground, where the greatest necessity for differential pressure is present, as the air at higher pressure would short-circuit into the lower pressure levels, making the device of no avail. In *Trans. Am. Soc. C. E.*, vol. 83, p. 447, a proposed differential air pressure shield is shown. The front edge of each working level of the shield is carried 18 in. ahead of that immediately above. The fundamental thought underlying this design is that the higher pressure air escaping from the lower levels will expand as it finds its way up and, therefore, will not increase the pressure in the upper levels. Any shield that maintains a higher air pressure at the face than that in the tunnel is open to the objection that the air in the comparatively small chamber in front of the shield will be exhausted quickly in case of a blow and expose the men in front to serious danger.

E. EXAMPLES OF TUNNEL SHIELDS

(A) Baker Street and Waterloo Railway, 1900–1901 (E-15)

72. Character of Ground.—The portion of the Baker Street and Waterloo Railway, which lies under the Thames, was built through waterbearing gravel.

73. Skin.—The outside diameter of the lining is 12 ft. 9¾ in. The shield (Fig. 64) had an outside diameter of 13 ft. and an overall length of 9 ft. 8½ in. The skin thickness at the tail was ½ in., making a clearance between the tail and the lining of 1¼ in. The skin consisted of a single thickness of steel plate, ½ in. thick extending the full length of the shield. Circumferentially there were six butt joints, spliced on the outside with cover plates, ½ in. thick.

74. Cutting Edge and Diaphragm.—The cutting edge, which was provided with a hood, covering the top and sides of the shield, was reinforced with three additional plates, ½ in. thick, and cut to bevel along the edge. Back of the hood the cutting edge was stiffened by an annular box-girder, made of rolled plates and shapes, and by a vertical plate at the center. The front diaphragm was located to the rear of and riveted to this stiffening structure. It extended from the top down to about the axis level of the shield and from the bottom up far enough to permit

the shield jacks to be inserted and replaced. The rear diaphragm was about 3 ft. back of the front diaphragm and was reinforced with three steel channels. The top of it was 6 in. above the lower edge of the front diaphragm in order to insure the necessary water seal. At a height of 2 ft. 9 in. above the lowest part of the shield the rear diaphragm was connected with the bottom piece of the front diaphragm by means of a steel plate, supported by brackets. This plate formed the floor of the water trap. To provide ready means of egress from the face, ladder rungs were fastened to the curved sides of the trap box as well as to the cutting edge.

75. Internal Structure and Jacks.—Immediately behind the front diaphragm and outside of the trap box was the usual segmental stiffening ring which, however, in this shield was made of steel castings, supporting the shield jacks. The jacks were 14 in number, but at variance with the usual practice were not spaced uniformly around the circumference. Eight of the jacks were placed in the bottom quadrant of the shield while the other six occupied the remaining part of the circumference. The jacks were of the piston type with leather packings. The diameter of the piston was 6 in. and of the piston rod 3½ in. The stroke was 22 in. The maximum hydraulic pressure was 2,400 lb. per square inch and the average working pressure was 1,300 lb. per square inch. During the working the four bottom jacks were rarely used, and under ordinary conditions only six jacks were needed to push the shield ahead.

76. Sliding Shutters.—When originally built the shield was provided with sliding shutters to support the face, of a construction similar to those used in the Blackwall tunnel shield. It was found, however, that owing to the small size of the shield the use of the shutters was not convenient and they were removed.

77. Face Struts.—In their place the shield was provided with four horizontal struts, passing through openings cut in the diaphragms. The struts consisted of steel tubes, 5½ in. in diameter and 7 ft. 6 in. long, plugged at both ends. The rear plug of each strut had a threaded hole in which turned a bolt, making the length of the strut adjustable. Where the struts passed through the diaphragms, leather sleeves were provided to make a tight joint. The front ends of the struts supported the poling of the face and the rear ends of the struts were in turn supported by cross timbers against the lining of the tunnel.

When the shield moved forward the struts would remain stationary holding the face undisturbed.

(B) PENNSYLVANIA RAILROAD HUDSON RIVER, 1904–1906 (A-18)

78. Character of Ground.—The type of shield used on the construction of the tunnels under the Hudson River for the Pennslyvania Railroad is shown in Fig. 63. While the greater part of these tunnels were driven through soft Hudson River silt, the shield had to pass through stretches where the ground was partly or altogether rock, and sand or gravel. The design of the shield was made with these conditions in view.

79. Skin.—The inside diameter of the tail of the shield was made 23 ft. 2 in. or 2 in. more than the outside diameter of the tunnel lining. The skin was made up of three thicknesses of steel plate, $\frac{3}{4}$ in., $\frac{5}{8}$ in. and $\frac{3}{4}$ in. thick, respectively, making the total thickness of the skin $2\frac{1}{8}$ in. and the outside diameter of the shield 23 ft. $6\frac{1}{4}$ in. The length of the shield, exclusive of the hood, was 15 ft. $11\frac{7}{16}$ in. The tail overlapped the tunnel lining a maximum of 6 ft. $4\frac{1}{2}$ in. during ordinary working and the minimum was 2 ft. during the operation of taking a jack out for repairs. There were no circumferential joints in the skin and the longitudinal joints were butt joints, covered by the adjoining plates and had no inside or outside cover plates. All rivets on the outside of the skin and inside the tail were countersunk.

80. Annular Box-girder.—For the purpose of erecting the shield in the restricted space underground the annular frame of the shield was fabricated in eight segmental pieces and the bulkhead of the shield was similarly made in suitable lengths for erection underground. The annular frame was made up of web plates at each end of the jack chambers and an inner skin plate, joined with angles. This box-girder was $23\frac{1}{2}$ in. deep radially and about 5 ft. long. Between the outer and inner skin plates were radial diaphragms extending the full length of the girder and riveted through angles to the skins and the end web plates. Forward of the front annular web plate this construction was repeated, except that the inner skin formed a truncated cone, being part of the cutting edge, and that an additional set of brackets was provided to take the thrust of the shield jacks.

81. Platforms and Partitions.—The structural framing of the bulkhead was kept as open as possible in the rear to permit the running of pipes within the framing. The four corner compartments formed by the platforms and partitions, which were closed

by means of diaphragms at the front, were also left open at the rear so as to have space available if needed. The cross bracing consisted of two horizontal platforms and of three vertical partitions on the two upper levels and four on the lowest level. The platforms, which extended to the front of the cutting edge, were constructed as box-girders, and the part of the partitions between two working compartments were of a similar construction, to make room for the various appliances of the shield. The other partitions as well as all the portions of the partitions in the cutting edge were of single plates reinforced at the front edge. The platforms and the partitions formed nine working compartments, two on the uppermost level, four on the middle level and three on the bottom level.

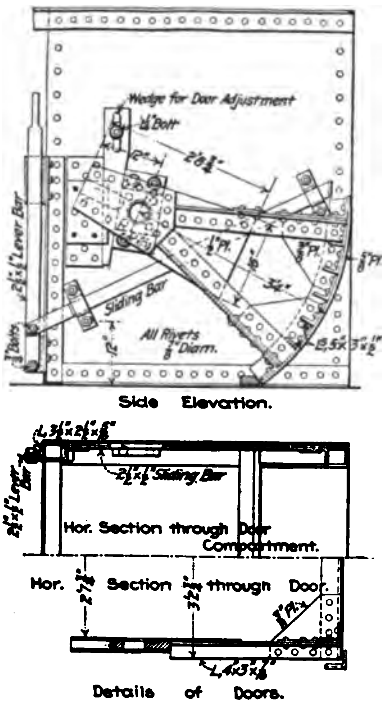


FIG. 81.—Pennsylvania Railroad Hudson River tunnel (A-18). Detail of shield doors. (From *Eng. News*, Dec. 13, 1906.)

82. Diaphragm.—The upper part of each of the compartments or pockets on the two lower levels was closed by means of a diaphragm, set at an angle of about 45 deg. and extending from the front of the cutting edge at the top of the pocket to the rear end of the cutting edge at about half the height of the poeket. In the topmost level similar diaphragms were placed vertically in the plane of the rear of the cutting edge.

83. Doors.—The doors used in this shield were of an unusual pattern (see Fig. 81). They were made in the shape of a segment of a cylinder and turned around pivots at the center of the cylinder. The door proper consisted of a steel plate, 5/8 in. thick, reinforced with angles. A triangular frame at each end of the segment formed the connection between the door and its pivots. A sliding bar on the one side of the compartment would

hold the door open as far as desired and a hand lever at the back of the partition made it possible to close the door immediately in an emergency by pulling back the bar and letting the door, which weighed 800 lb., drop by its own weight.

84. Cutting Edge and Hood.—The cutting edge was provided with a shoe of steel castings, made in segments and bolted to the structure. This shoe extended all around the circumference,

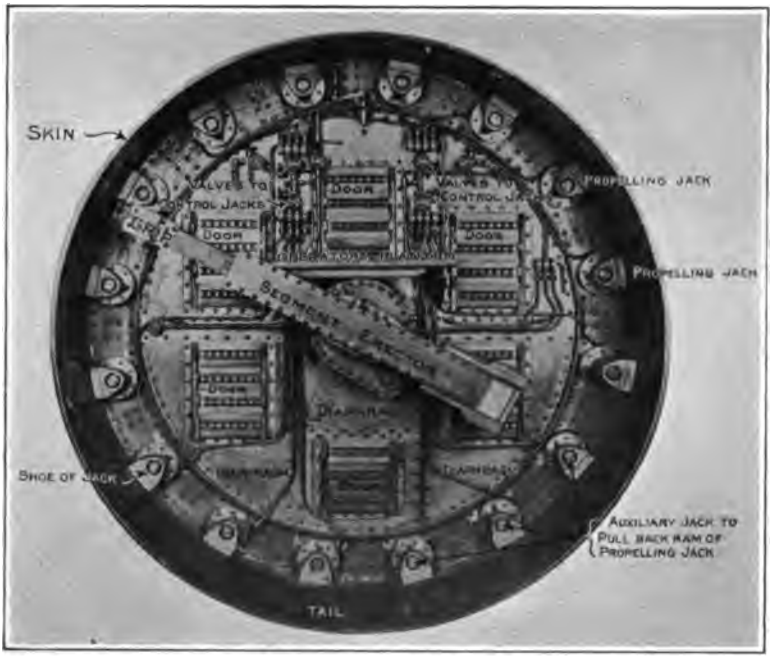


FIG. 82.—The parts of a shield. Rear elevation.

except when the detachable hood was used. The purpose of making the hood detachable was, that while it was needed when the shield passed through materials other than silt, it would be inconvenient while driving through the silt and particularly so when the shields driven from opposite sides of the river met in the soft silt. The hood was arranged, therefore, so that it could be removed when the shield was about to enter the silt. The hood projected 2 ft. 1 in. beyond the cutting edge and covered the top as far down as to the upper platform of the shield. It was built up in nine sections of the same thicknesses of plates as the skin and was fastened by interior splice plates. At each junction of

12

the sections of the hood it was supported by brackets extending back and attached to the steel structure.

85. Face Jacks.—In each of the platforms were placed four pairs of hydraulic jacks acting as face supports and supports for sliding platforms, which could be extended 2 ft. 9 in. viz.: 8 in. in advance of the hood. The platforms were strong enough to carry a load of 7,900 lb. per square foot, this being equivalent to the maximum combined head of water and ground. The plunger head of

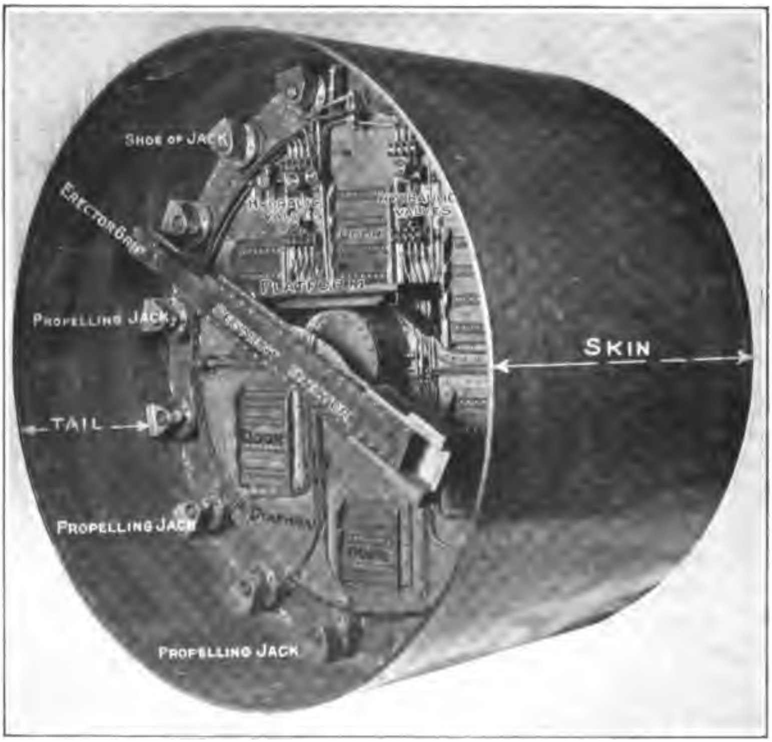


FIG 83.—The parts of a shield. Rear perspective.

each of the jacks was fastened to and supported against the rear part of the box-girder forming the platform. The jack cylinder was square in outside cross-section and could slide through two bearings under the floor. At the outer end of the cylinder was bolted a casting or nosing which extended up flush with the floor of the platform, and a steel plate attached to the nosings of each pair of cylinders formed the sliding platform. The platform

jacks were single acting, had a diameter of 3½ in. and a stroke of 2 ft. 9 in. At a hydraulic pressure of 5,000 lb. per square inch each jack could develop a thrust of 48,000 lb.

86. Shield Jacks.—The propelling jacks, of which there were 24 and which are shown in Fig. 70, had a plunger diameter of 8½ in. The jacks were tested to a pressure of 6,000 lb. per square inch and were intended to be used with a maximum working pressure

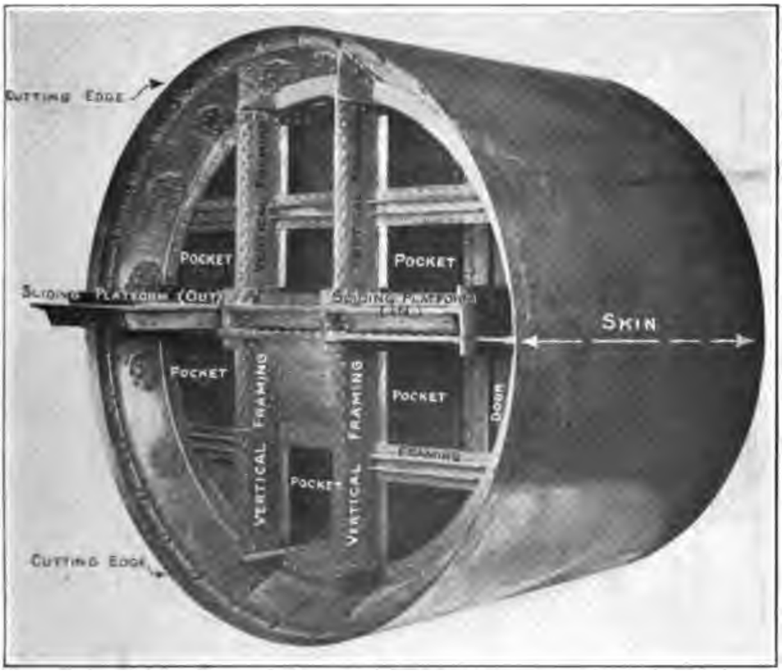


Fig. 84.—The parts of a shield. Front perspective.

of 5,000 lb. per square inch. The average pressure used was 3,500 lb. per square inch. The following are some leading figures relating to the shield jacks with a water pressure of 5,000 lb. per square inch:

	Pounds
Forward thrust of 1 jack	27,500
Forward thrust of 24 jacks	660,000
Equivalent thrust per square foot of face	15,200
Pull-back thrust of 1 jack	26,400

In order to facilitate the placing of the jacks, the bearing casting at the front end of the jack was provided with a long flaring socket, which guided the casting into its proper seat.

87. The Segment Erector.—The segment erector revolved around a shaft centred on the axis of the shield. It consisted of a box shaped frame enclosing a double acting hydraulic jack with plungers 4 and 3 in. in diameter. To the head of the plunger was attached two channels which could slide outside the box frame and carried the bending stress. The opposite end of the box frame carried a counterweight which balanced about 700 lb. at a radius of 11 ft. The erector was revolved by two single acting jacks, fixed horizontally to the back of the shield platform, through double chains and wheels. The following figures relate to the erector:

	Pounds
Weight of heaviest tunnel segment	2,584
Weight of erector plunger and grip	616
Total weight handled by the erector	3,200
Maximum outward thrust on erector at 5,000 lb. per sq. in.	35,000
Maximum inward thrust on erector at 5,000 lb. per sq. in.	27,500
Total pressure on each rotating jack	80,000

88. Controlling Valves.—The hydraulic equipment was controlled from a special platform placed behind the main platform above the erector rotating jacks and formed a protection for these. All operating valves were placed within reach of this platform.

CHAPTER X

PLANT AND EQUIPMENT IN TUNNEL

1. Items of Plant and Equipment.—In addition to the tunneling shield—discussed in the previous chapter—the following items of plant and equipment are needed and used in the construction of a tunnel.

(*A*) The low pressure air equipment for transmitting the compressed air from the power house into the portion of the tunnel (or "air chamber") in which the work is carried out under air pressure.

(*B*) The high pressure air equipment for transmitting the compressed air used for power tools, grouting, etc. from the power house into the tunnel.

(*C*) The hydraulic power equipment for transmitting the hydraulic power used on the shield from the power house to the shield.

(*D*) The service water supply for cleaning and other purposes.

(*E*) The lighting equipment for the tunnel.

(*F*) The telephone equipment, connecting the tunnel with the offices.

(*G*) The pumping plant.

(*H*) The transportation plant and equipment.

(*I*) The excavation equipment.

(*J*) The working platform immediately behind the shield.

(*K*) The equipment used for bolting up the tunnel lining.

(*L*) The grouting plant.

(*M*) The air bulkhead and air locks.

(*N*) The safety appliances for use in compressed air.

The items as enumerated cover the plant and equipment needed for a tunnel driven under compressed air. For a tunnel driven in normal air the items *A*, *M*, and *N* are not included. The item *K* applies particularly to cast iron lined tunnels.

A. LOW PRESSURE AIR EQUIPMENT

2. Definition of Low Pressure Air.—By the low pressure air is understood air compressed to a pressure greater than atmospheric, introduced into a tunnel and confined therein during

construction to counteract the tendency of water or ground to flow into the excavation.

3. Equipment in Tunnel.—As far as the tunnel is concerned the low pressure air equipment is limited mainly to piping for conveying the air from the power house to the air chamber. The compressor plant is discussed in Chap. XI.

4. Size of Pipe.—The volume of air to be delivered is discussed in Chap. XI. The size of pipe required to convey a given volume of air may be determined approximately by the equation

$$(p_1^2 - p_2^2)d^5 = 0.0005Q^2L \qquad (36)$$

where

d = the diameter of the pipe in inches.
Q = the equivalent volume, in cubic feet, of free air per minute passing through the pipe.
L = the length of the pipe in feet.
p_1 = absolute initial air pressure in pounds per square inch.
p_2 = absolute terminal air pressure in pounds per square inch.

For any given tunnel work the values of p_2, Q and L in equation (36) are predetermined. There remain d and p_1, either of which may be chosen arbitrarily within certain limits and the other determined by the equation. If d is chosen small, the pipe line will be economical in construction, but the cost of the compressor plant will be higher than if a larger pipe diameter was chosen. If p_1 is chosen so that $p_1 - p_2$ is small then the compressor plant will be economical, but the cost of the pipe will be higher.

5. Loss of Pressure by High Velocity.—Usually it is better to choose p_1 so that the $p_1 - p_2$ is small for the average supply of air required. Then if the time comes when an emergency supply of larger volume is required, it will be possible to convey it through the pipe without excessive loss of pressure. The smaller the pipe provided to transport a given volume of air, the higher is the velocity of the air in the pipe and the greater is the resulting loss of pressure in the pipe. As an example, Fig. 85 shows the relationship between the diameter of pipe and the loss of pressure when 4,800 cu. ft. of free air per minute are delivered through a pipe 1,000 ft. long at a terminal pressure of 30 lb. gauge pressure per square inch. The range of pipe diameter shown is from 7 to 15 in. The figure shows that for a pipe diameter of 13 in. or more the pressure loss is insignificant, while for smaller diameters

the loss of pressure rapidly increases with a decrease of the pipe diameter. In other words, the pressure required at the compressor is increased.

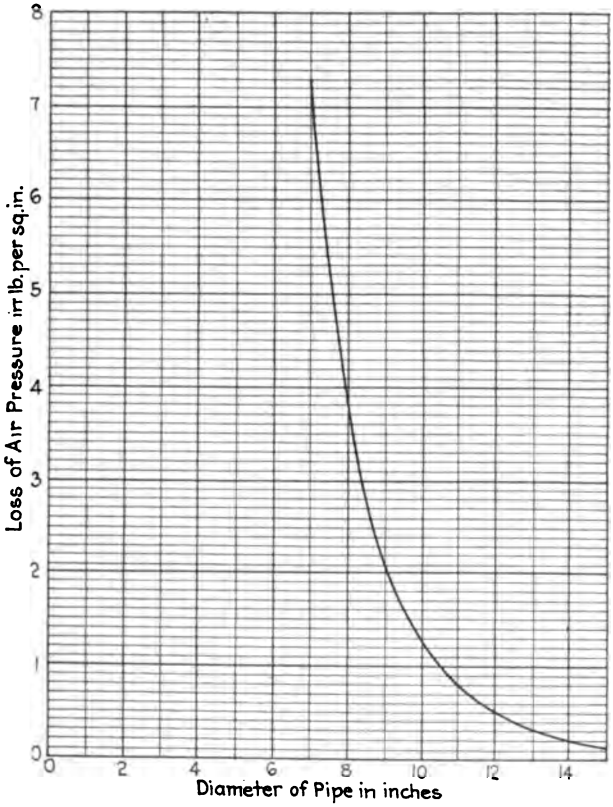


FIG. 85.—Relationship between diameter of pipe and loss of pressure for a specific case. (4,800 cu. ft. of free air per minute through 1,000 ft. of pipe at a terminal pressure of 30 lb. per square inch.)

6. Pipe Diameter in Open Waterbearing Ground.—In Chap. XI it is stated that in open waterbearing ground the average supply of air may be expressed by

$$Q = 12D^2 \tag{37}$$

where D is the external diameter of the tunnel in feet. In case of a blow the necessary supply may be doubled or even trebled. If the initial air pressure p_1 is selected so that

$$p_1 = p_2 + 1$$

then approximately

$$p_1^2 - p_2^2 = 2p_2 \tag{38}$$

Inserting in equation (36), the value of Q as determined by (37) and the value of $p_1^2 - p_2^2$ as determined by (38) then this will read

$$d^5 = \frac{0.036D^4L}{p_2} \tag{39}$$

If it is desired to use two pipes instead of one to carry the air, the diameter of each pipe will be determined by

$$d^5 = \frac{0.009D^4L}{p_2} \tag{40}$$

and if three pipes are used the diameter of each is

$$d^5 = \frac{0.004D^4L}{p_2} \tag{41}$$

The values of p_2 used in these equations should be the average air pressure that it is expected will be used and not the highest, because the air is transported with less loss of pressure when the air pressure is higher. It should be remembered that the air pressure in the equations is the absolute air pressure, which is 14.7 lb. higher than the gauge pressure.

7. Table of Pipe Diameters in Open Ground.—Table XII shows the pipe diameters computed from equations (38), (39) and (40) when the terminal air pressure is 40 lb. per square inch, for tunnels varying in diameter from 5 to 35 ft. and in length from 1,000 to 10,000 ft.

TABLE XII.—DIAMETER OF LOW PRESSURE AIR PIPE FOR TUNNELS IN OPEN WATERBEARING GROUND

	Diameter of pipe in inches											
	$L = 1{,}000$ ft.			$L = 3{,}000$ ft.			$L = 5{,}000$ ft.			$L = 10{,}000$ ft.		
	Number of pipes			Number of pipes			Number of pipes			Number of pipes		
	1	2	3	1	2	3	1	2	3	1	2	3
5	3.6	2.7	2.3	4.4	3.4	2.9	4.9	3.8	3.2	5.6	4.3	3.7
10	6.2	4.7	4.0	7.7	5.9	5.0	8.5	6.5	5.5	9.8	7.4	6.3
15	8.6	6.5	5.5	10.7	8.1	6.9	11.8	9.0	7.6	13.5	10.3	18.7
20	10.8	8.2	7.0	13.4	10.2	8.7	14.9	11.3	9.6	17.1	13.0	11.0
25	12.9	9.8	8.3	16.1	12.2	10.3	17.8	13.4	11.3	20.4	15.5	13.2
30	14.9	11.3	9.6	18.5	14.1	12.0	20.5	15.6	13.2	23.5	17.9	15.2
35	16.9	12.7	10.9	21.0	15.9	13.5	23.3	17.6	15.0	26.7	20.2	17.2

The table indicates that it is more economical to carry the air in one pipe rather than in several pipes.

8. Emergency Supply of Air.—In case of an emergency the pipe diameters as determined above will permit the furnishing of twice or three times the normal volume of air without excessive loss of pressure. The double quantity can be carried with a loss of 3.8 lb. and three times the quantity with a loss of 8 lb.

9. Diameter of Pipe in Close Ground.—In close ground where the volume of air is determined by the requirements of ventilation only, the diameter of the pipe required will be less than as given above. The size of pipe required can be determined by equation (35), when the volume needed is known.

10. Size of Pipe Actually Used.—Table XIII shows the size of air pipes actually used in various tunnels driven under compressed air.

TABLE XIII.—SIZE OF LOW PRESSURE AIR PIPES USED

Ref. No.	Tunnel	Diameter in feet	Air pipe: Diameter in inches	Air pipe: Number of pipes
(E-17)	Rotherhithe	30.00	10	2
(E-17)	Rotherhithe, Pilot	12.50	10	1
(E-11)	Greenwich	12.75	12	1
(A-19)	P. R. R. East R.	23.00	8	2
(A-18)	P. R. R. Hudson R.	23.00	10	1
(F-12)	Concorde Met	25.51	12	1
(E-7)	Blackwall	27.00	8	2
(E-13)	Lea	12.00	10	1
(A-5)	Sarnia	21.00	6	1
(A-27)	Old Slip	17.08	10	2
(A-28)	Whitehall	18.00	10	2
(A-30)	14th St., East River	18.00	10	2
(A-35)	60th St., East River	18.00	10	2

11. Sub-division of Pipe.—In order to avoid excessive pipe diameters, the piping may be sub-divided into two or more pipes. Each pipe should be calculated for the proportion of the volume of air to be carried by the pipe. From Table XIII it will be noticed that several of the larger size tunnels were provided with two air pipes.

12. Length of Pipe.—In some tunnels the low pressure air pipes have been terminated just inside the compressed air chamber. They should be carried, however, as close as possible to the shield and extended as the shield advances in order to ventilate the air chamber at the point where the men are at work. This is particularly important when the ground is so close that the air does not escape in large volumes through the ground.

13. Duplication of Pipe.—It is sometimes specified that the air supply pipe shall be installed in duplicate, so that an uninterrupted air supply may be assured. While this may seem a serious item of expense it should be looked upon as an investment for safety. The uninterrupted air supply is vital not only for the men working in the tunnel, but also for the tunnel itself. The duplicate may never be called upon to be used, but if occasion should occur, it may save the day. It is scarcely necessary to carry this duplicate any further than just inside the air chamber.

14. Branch Pipe at Air-lock.—It is prudent to bring a branch off the air pipe at the normal side of the bulkhead wall (see par. **89**) and to carry this branch through and end it just inside the wall. In this way the air pressure could be maintained if stoppage occurred in the pipe leading to the shield.

15. More Than One Bulkhead.—In tunnels having more than one bulkhead and maintaining different air pressure between the bulkheads from that at the face, a branch should be taken off the air line at the bulkhead and provided with a valve for replenishing and purifying the air in the chamber between the bulkheads.

16. Construction of Piping.—Spiral riveted or standard lap welded pipe is generally used for the low pressure air supply. The joints are flanged with rubber gaskets between the flanges. A flap-valve is attached to the discharge end of the pipe. It is most important to see that this is replaced every time the pipe is lengthened.

17. Location of Pipe.—The pipes are carried along the sides of the tunnel supported by brackets or slings to the lining. They are placed as far as possible away from the track in the tunnel so that risk of damage or breakage by an overturned car may be a minimum.

18. Condition of Pipe.—Results approaching those computed will be gained only by use of pipe with smooth interior surface, at the joints as well as in the pipe itself, by use of bends of large

radius, by avoidance of low points in which water may collect, and in short by giving the pipe every chance to do its work under the best conditions.

19. Safety Valves.—At the bulkhead walls, safety valves set to blow off if the pressure rises above that desired should be provided.

20. Regulation of Pressure with Tide.—When the air pressure must be regulated with the tide, a schedule may be prepared for the power house with the pressure required at each hour. A better method is to use recording tide gauges from which the pressure is regulated according to a schedule showing the relationship between tide and pressure required. At some works, an automatic arrangement opening and closing a valve on the supply pipe has been used.

21. Caution Regarding Pressure in Tunnel.—James Brown, one of the most experienced tunnel men in Great Britain, has stated (*Proc. Inst. C. E.*, vol. 175, p. 224) that "he believed accidents in compressed air tunnels were more frequently caused by too much pressure than by too little. Workmen in tunnels, seeing a drop of water at the face, were always ready to shout for more air, and if they got it, were apt to blow a hole in the top and let the air out." This remark should be noted by all engineers responsible for compressed air work. It is the fruit of a great experience.

22. Foul Air Pipe.—A foul air blow-off pipe should be laid from near the shield to the bulkhead wall and out to normal air. If the ground is not permitting the air to escape, the proper ventilation can be had by opening the valve in this pipe. The foul air pipe is rather smaller in diameter than the supply pipe. The usual size is from 4 to 6 in. in diameter.

B. HIGH PRESSURE AIR EQUIPMENT

23. Definition.—The high pressure air is that used for operating tools, such as drills and calking hammers, for grouting purposes and for hoisting machines operated by compressed air.

24. Air Pressure.—The working tools are usually made to work at a pressure of about 90 lb. above normal atmospheric pressure. In tunnels driven in normal air, the high pressure air should be delivered, therefore, at this pressure. In tunnels driven under compressed air the pressure should be higher by the degree of air pressure which is carried in the tunnel. For

grouting purposes a similar pressure is generally suitable, but in some cases the pressure needed is higher.

25. Size of Pipe.—Usually a 3- or 4-in. standard steam pipe with screwed connections or flanges with rubber gaskets is used for the high pressure air. If much air is to be used for drilling or operating air tools the high air line may have to be as large as 8 in. or 10 in. in diameter. T-connections are provided at intervals. It is important to put in plenty of connections. They may be needed and it is easier to place them when the pipe is erected than to have to disconnect the pipe later.

26. By-pass.—It may be useful to make a by-pass from the high to the low pressure line, so that in case of an emergency the high pressure air may be used to boost the pressure in the air chamber.

C. THE HYDRAULIC POWER EQUIPMENT

27. Purpose.—The hydraulic power is used for operating the hydraulic equipment of the shield, which includes the shield jacks, the face jacks and the segment erector.

28. Method of Conveyance.—The water may be carried either under the full working pressure or at a more moderate pressure from the power house to the shield. In the latter case the pressure is raised by an intensifying pump at the shield.

29. Working Pressure.—While in the earlier shields the working pressure rarely exceeded 1,800 lb. per square inch, the present tendency is to make the hydraulic equipment capable of carrying a pressure of from 5,000 to 6,000 lb. per square inch or even more. This pressure, however, is generally used only when the conditions necessitate it and the working pressure is usually about 3,500 lb. per square inch.

30. Piping.—The piping is made of extra heavy hydraulic pipe of an inside diameter of from 1⅛ to 1½ in. with wall of ⅜ to ½ in. thickness. The couplings are either cast iron or steel castings with screw thread and having a hexagonal cross-section at the middle, so that they may be tightened with a bolt wrench, or they are flanged with leather packings.

31. Connection at Shield.—The piping is kept as close to the shield as conveniently possible. From the end of the pipe line a flexible high pressure armored hose or a copper pipe is used to make connection with the main valve box on the shield, which

is advancing while the hydraulic pressure is on the jacks. Strainers should be placed in the piping near the jacks to prevent scale and other impurities from entering and damaging the jacks.

32. Safety Valve.—A safety valve is placed on each main so that the pressure on the jacks may be cut off instantaneously without danger of bursting the pipe.

33. Duplicate of Piping.—In some cases the piping for the hydraulic power is duplicated as a precaution against delays due to damage to the piping. This practice is recommended.

D. THE SERVICE WATER SUPPLY

34. Purpose.—In addition to the hydraulic power supply a water supply at the ordinary service pressure should be furnished for grouting, cleaning and similar purposes.

35. Piping.—The piping for the service water supply may be a 4-in. pipe and should have T-connections at regular intervals of 100 to 200 feet throughout the tunnel. It is advantageous also to have connections in the air locks.

36. Fire Connections.—In towns having fire protection service it is well to install standard fire department hose connections at the bulkhead walls and near the shield so that a serious fire may be dealt with by the fire department. Fire is one of the most dangerous hazards in a compressed air tunnel especially where much timber is being used and most especially where hay and straw are used to pack behind the timbers. The smallest spark from an electric motor or a match may be enough to kindle a most serious fire and there should be rigid rules against the men smoking in a compressed air tunnel and the most ample arrangement made for fighting a fire if one should start. See *Trans. Am. Soc. C. E.*, vol. 69, page 36.

E. ELECTRIC LIGHT AND POWER EQUIPMENT

37. Power Service.—The wiring needed for the power service depends on the electric power equipment in the tunnel. If electric transportation is used the current is usually taken from a bare trolley wire strung high enough to make passage through the tunnel safe. About four pipes should be built in the bulkhead walls to carry the electrical cables. They should not be less than 1½ in. diameter.

38. Lighting Service.—The wires for the lighting service are strung along the roof and the sides of the tunnel on insulated supports. Outlets are provided at intervals so that flexible leads may be connected for use at points where work is in progress. Lights should be provided and kept burning throughout the tunnel. At the locks, at the shield and at other points where work is in progress additional lights should be provided. These lights may be in groups of three, five or more lamps in clusters with reflectors, so that the working space is well lit.

39. Spacing and Candle Power of Lights.—It is false economy to cut down the lights in the tunnel to such an extent that the work is made dangerous or hindered. It is better to use a lamp of moderate candle power, such as 16 c. p., and to space these lamps closer than to use high powered lamps spaced far apart. This latter arrangement gives dark shadows which the other avoids. It is found that a fair working lighting is given by allowing about 0.05 candle power per square foot of interior tunnel in plan measured at its axis level.

40. Example.—On the Hudson River tunnels of the Pennsylvania Railroad (A-18) one row of 16 candle power lamps at 30-ft. intervals was placed along the roof of the tunnel. Another row of 16 candle power lamps, also at 30-ft. intervals, was strung along the one side just above the axis level. The lamps of this row were spaced halfway between those of the top row. The upper row lit the suspended emergency runway and the lower row lit the working floor and track.

41. Reflectors.—All lights should have reflectors so that the light is not thrown in a useless direction. These may be of metal or of wood, painted white.

42. Arc Lights in Normal Air.—Where tunneling is carried out in normal air arc lights are useful. The light given by these lamps is much better than that of incandescent lamps.

43. Rough Usage.—The lamps in the tunnel, especially those used at the working points are subject to rough usage. All lamps should have a wire guard over the bulb.

F. TELEPHONE

44. Purpose of Telephone.—In every tunnel there should be ample telephone connection between the working chamber and the surface offices, power house, repair shop, etc., so that the man

in charge below can keep in touch with his sources. So essential is the telephone to the proper conduct of tunnel work that in most specifications now there is a clause requiring the provision and maintenance of a telephone connection from each shield and lock to the surface offices. The telephone is attached to the wall of the tunnel and is enclosed in a waterproof box. A loud ringing bell is convenient.

G. THE PUMPING PLANT AND EQUIPMENT

45. Blow-out Pipe.—In a compressed air tunnel the water is removed from the invert of the working chamber by means of the blow-out pipe, which is a pipe, from 4 to 6 in. in diameter, leading from the shield back through the bulkhead wall to the sump and pumping station at the foot of the shaft. A length of flexible hose with a strainer is attached to the forward end of the pipe, and a valve is provided for closing the pipe. When the hose with the strainer is immersed in the water to be removed and the valve is opened, the air pressure in the working chamber forces the water through the pipe to the sump.

46. Examples.—On the Blackwall tunnel (E-7) three 5-in. blow-out pipes were used and on the Pennsylvania Railroad tunnels under the Hudson River (A-18) two 6-in. pipes. The Old Slip (A-27), Whithall (A-28) and 14th St. (A-30) tunnels had each one 6-in. blow pipe. The 60th St. tunnel (A-35) had two 6-in. pipes.

47. Excavation and Removal of Spoil by Blow-out Pipes.—In wet sandy ground a great deal of the excavation in the lower pockets of the shield may be done with the blow-out pipes.

48. Pumping Plant at Shaft.—For lifting the water from the sump at the bottom of the shaft to the surface, any reliable kind of pump may be used. The water discharged by the blow-out pipe may be charged heavily with sand so that either the pump must be able to handle this or an ample settling basin must be provided.

49. Removal of Water under Normal Air Pressure.—When the tunnel is driven under normal air pressure, a pumping plant must be provided for removing the water from the face of the tunnel. The pump should be transportable and always placed near the shield so as to have sufficient suction.

50. Capacity of Pumps.—The capacity of the pumps which should be supplied is mostly determined by judgment. As a

rough guide and judging from previous experience it may be said that a stand-by or emergency pump of 500 gal. per minute capacity should be provided for each heading with a smaller unit of from 100 to 140 gal. capacity to take care of routine water. The pumps should be simple of construction and reliable and may be driven by electric power or compressed air.

H. THE TRANSPORTATION PLANT AND EQUIPMENT

(A) The Track System

51. Floor.—In order to support the track, some kind of floor is needed in the tunnel. In the smaller size tunnels it has been the habit to fill in the invert with material excavated from the face. This is not a good method. If the material used as fill is clay it will become soft and wet and form a poor foundation for the track. Furthermore, it is difficult to remove. In cast iron lined tunnels the many flanges crossing each other at right angles and the bolts form projections at short intervals. Special tools and scrapers have to be used and much water and scrubbing required before the tunnel is clean and fit for the permanent finish.

52. Wooden Floor.—The most suitable floor construction is one of wood. Wooden joists are placed crosswise in the tunnel at regular intervals and supported on the tunnel lining. If necessary, posts may be placed to support the joists. Planking is laid longitudinally over the joists and the ties of the track spiked to the planking or joists.

53. Width of Floor.—When the size of the tunnel permits, the width of the floor should be enough for a double track. The Rotherhithe pilot tunnel, which had an outside diameter of 12 ft. 6 in., had a roadway with a clear width of 8 ft. 6 in. This allowed room for two tracks with cars having an overall width of 2 ft. 9 in. In the Pennsylvania Railroad Hudson River tunnels (A-18) the floor had a clear width of 20 ft. The outside diameter of the tunnel was 23 ft.

54. Height of Roadway.—In most cases the roadway is placed as near to the invert as compatible with the desired width. This is done partly as a matter of economy and partly to have as much headroom as possible. When the tunnel is large enough it is desirable not only to have headroom for the main deck, but also for an emergency gangway above. Furthermore,

it is desirable to have the floor low so that the excavated material may be loaded into the cars without excessive lift. There are some other aspects of this matter, which generally are not considered.

55. Emergency Gangway.—One of these points is that of an emergency gangway in a small diameter tunnel. The purpose of this gangway, which will be described more fully later, is to provide a passage from the shield to the bulkhead wall as far above the invert as possible, so that in case of a blow at the face, the men will have an opportunity to escape while the lower part of the tunnel is filling, but while the upper part is still clear. In a small tunnel there is no headroom for such a runway above the roadway and, consequently, it is left out. It is worth considering whether the roadway might not be placed so high above the invert that it would have the same effect as an emergency runway, instead of placing it as near as possible to the invert. Incidentally it may be noted that the possibility of the tunnel being flooded is another reason for not filling the lower part solid with spoil to form a support for the construction tracks.

56. Inspection of Lower Part of Tunnel.—Another point with regard to the height of the roadway is connected with the inspection of the lining. In Chap. XIII it is stated that careful and complete inspections should be made of the tunnel lining at regular intervals and also that the bolts in the joints of a cast iron lining should be tightened from time to time, because they work loose on account of the construction conditions. In a tunnel with the construction track at its usual level, this work is practically precluded for possibly one-third of the circumference on account of the small space left between the floor and the invert.

57. Proper Height of Roadway.—For the reasons stated the roadway in a small tunnel should be placed as high as the necessary headroom will permit, and in a large tunnel at a level of from 5 to 6 ft. above the invert so that reasonable opportunity is afforded for getting at the portion of the lining below the roadway. The height of the roadway is generally left entirely to the contractor and he is apt to place it low, because it is most economical in the first instance. The importance of having it located at the proper height, however, may be sufficient to make it a matter to be included in the specifications.

58. Height of Roadway at Shield.—At the shield a low roadway is desirable. This might be attained by building the floor

construction only as far as to the rear of the trailing platform behind the shield and make this platform carry the floor for the portion covered by its length.

59. Track Gauge.—The minimum gauge of the construction track should be 24 in., and a gauge from 30 to 36 in. has many advantages as regards stability of the cars. An overturned car is a source of serious delay. The size of the tunnel has naturally an important bearing on the gauge possible.

60. Double Track.—In a tunnel there areconstant streams of cars going in and out to take care of the excavated spoil and another stream of cars taking in the lining materials. Whenever the tunnel is wide enough there should be provided two main tracks throughout the tunnel. When driven under compressed air there is a delay taking the cars through the locks. If possible two material locks should be provided so as to impede the traffic as little as possible. In addition to the main tracks there should be sidings for storage of empty cars and of cars loaded with lining materials, so as to have no delay from waiting for cars. Figure 86 shows a general arrangement of tracks, sidings and switches in a compressed air shield driven tunnel.

61. Maintenance of Track.—Great care should be given to the laying and maintenance of the track. More time and money is often wasted in derailments caused by a track improperly laid and maintained than the saving in first cost which is made by using an inferior track construction. The track should be kept to line, gradient and gauge. A proper design of switches and turn-outs should be used and properly laid. The rails should be of sections of not less than 25 to 30 lb. per yard. Economy in the track construction will soon be eaten up by delays due to "car off the track" and general demoralization of the transportation. The track should be spiked to the floor beams and not to the planking, because the flooring can then be removed without disturbing the track.

(B) The Cars

62. Use of Cars.—The cars used in tunnel transportation are mainly used for taking out the excavated spoil and for bringing in the lining. Special types of cars are used for each purpose.

63. Muck Cars.—The cars used for taking out the spoil, or the muck cars, should be of rather small capacity. The excava-

tion is not carried out on a large scale as it is with a steam shovel in a railroad cut and the cars have to be handled by man power at and sometimes through the shield as well as through the locks.

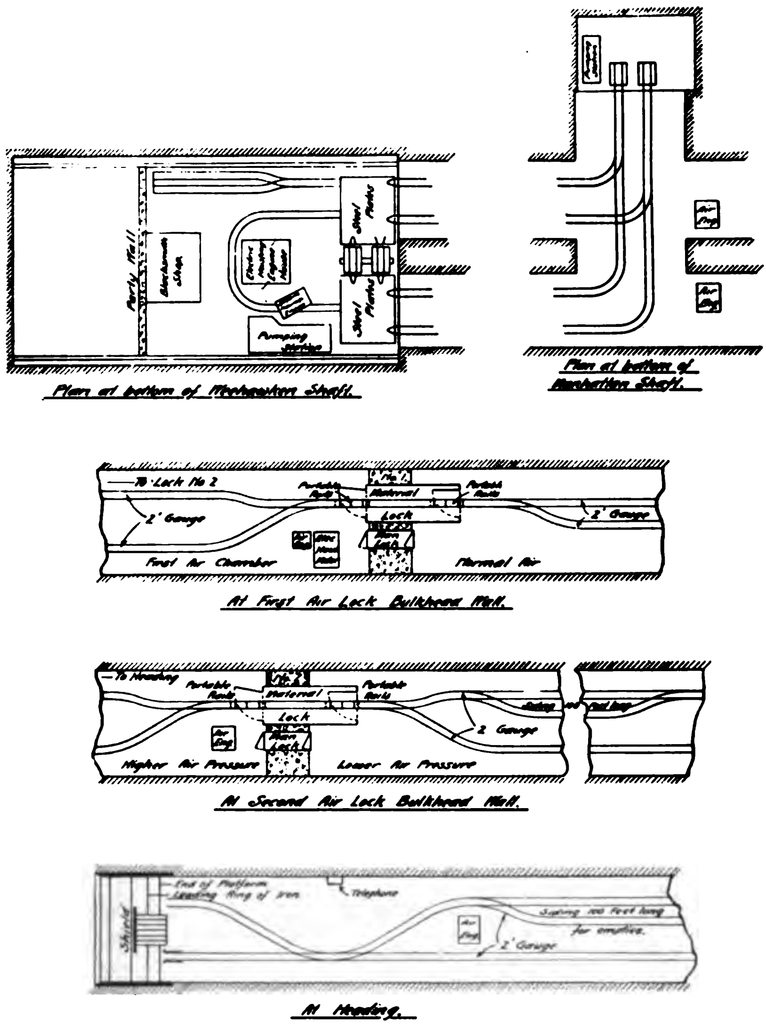


FIG. 86.—Plans of tracks, sidings and switches in a compressed air tunnel (A-18).

A suitable capacity is a cubic yard more or less. They should not be too wide, because they have to be taken through the locks; a width of 3 ft. would usually be about right. The body of the car should be low and set low on the trucks, so as to make the

reach in shoveling as low as possible. A length of the car body of about 5 ft. will generally be suitable. A short wheel base is advantageous for turning the car around sharp curves, but it should not be so short as to be easily upset. Side- or end-dump

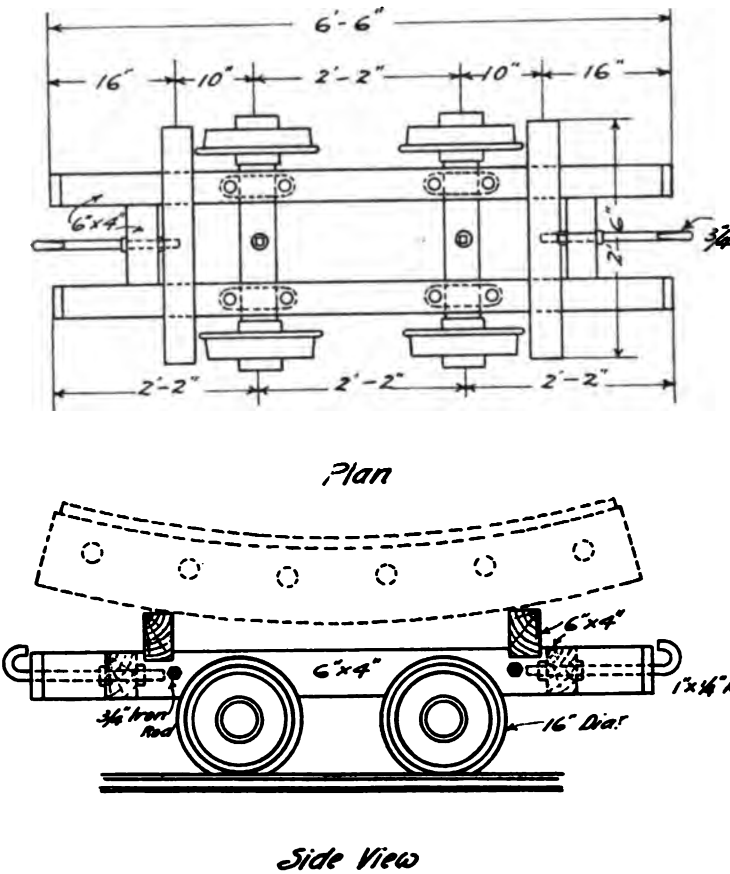


FIG. 87.—Car used for carrying segments of cast iron tunnel lining. Tunnel (A-18).

cars are equally satisfactory; the kind to select is determined by the arrangement of the dump. Cars are made of steel or wood, reinforced with steel. The latter is perhaps the best, because such cars can be repaired more readily on the job than can those of steel.

64. Material Cars.—The material cars are used for taking in the lining materials. Owing to the heavy loading they may have

to carry they should be built sturdily. The car body may consist of two longitudinal timbers set on the frame of the trucks with two cross bolsters set at the ends in such a manner that the curved outside of the segments is supported by them. Figure 87 shows a car used for carrying cast iron lining.

(C) Haulage System

65. Methods Used.—Various haulage systems are used in tunnels, depending somewhat on the size and length of the tunnel. In small tunnels, particularly when the length is short, the cars may be pushed by hand. In larger and longer tunnels mules or ponies are sometimes used. Animal power should be avoided whenever possible. Mechanical systems of haulage are better.

66. Air Locks.—In tunnels driven under compressed air the air bulkheads form barriers for mechanical haulage, and most systems require the cars to be pushed by hand through the air locks. The mechanical haulage system consists, therefore, of a series of independent units, one from the shaft to the first lock, one between each of the succeeding locks and one from the last lock to the face.

67. Rope Haulage to and between Locks.—From shaft to lock and between locks the distance is fixed. When rope haulage is used the plant consists of a hoisting machine driven by electricity or by compressed air, operating a continuous cable. The cars are provided with grips by which each car can be attached to the cable, which is continuously moving. The cable should be at least $\frac{5}{8}$ in. and preferably $\frac{3}{4}$ in. in diameter. Fifteen cars per hour have been handled each way up and down a 2 per cent gradient by this system.

68. Rope Haulage to Face.—As the shield is continuously advancing the distance between the last air lock and the face is continuously increasing. Rope haulage in this part of the tunnel is conveniently arranged by installing an electrically or air driven hoisting engine near the bulkhead, which hauls the cars singly or in trains by a cable. This system is most satisfactory when the tunnel is on a down gradient, so that the cars will move to the shield by force of gravity, held in check by the cable. Otherwise, another hoisting engine must be placed at or near the shield and it must be moved forward as the shield advances.

69. Electric Haulage.—In the case of electric haulage a bare conductor is placed through the tunnel high enough to clear the heads of men walking in the tunnel, and small locomotives are used to haul the cars. This gives a compact, self-contained unit and has many advantages, including the possibility of handling the trains through the locks by means of the locomotive. The drawback to the system is the bare conductor, although means can be provided to decrease this difficulty (see Fig. 88).

FIG. 88.—Electric locomotive with overhead trolley wire in tunnel. (Courtesy of *Hudson and Manhattan Railroad*.)

70. Other Methods of Haulage.—Compressed air and storage battery locomotives would do the work, but their weight requires a heavy floor and track system. Nevertheless, constant improvements are being made with these machines and it may be worth inquiring into them for a given project.

I. THE EXCAVATION EQUIPMENT

71. Mechanical Excavators.—In Chap. IX several mechanical excavating machines which have been used in connection with soft ground shield driven tunnels are described. These machines are most suitable in ground of a uniform character and only when it is self sustaining.

72. Rock Drills.—For tunneling through rock the present tendency is to use the small type of hand drills instead of the heavy

Fig. 89.—A tunnel shield at the end of its journey. This shield has come a distance of 4,500 ft. from the Hudson River to 6*th* Avenue, New York. 2,000 ft. of its course were in rock. 26,000 sticks of dynamite were used in blasting ahead of the shield. (Courtesy of *Hudson and Manhattan Railroad.*)

tripod type so universally used a few years ago. This is on account of the greater flexibility of use obtained by the small drill and by the fact that the cramped quarters in front of the shield make a small tool more convenient to use than a large one. The charge per hole with these drills is also lighter and the rock is broken smaller and more gently, which tends to prevent injury

FIG. 90.—Another battered veteran. (Courtesy of *Hudson and Manhattan Railroad.*)

to the shield. A shield is able to stand a lot of punishment (see Figs. 89 and 90) but it is well not to presume on this ability too far.

73. Equipment for Soft Ground Excavation.—For clay, sand and gravel the ordinary picks, bars, slices, etc. will be required as well as a good supply of planks and dimension timbers for props, stretchers, walings, soldiers and other members of support for the sheathing. In stiff clay a draw knife, formed of a piece of hoop iron bent to a curve and provided with handles, has been

found the most efficient tool for getting out the excavation. In open ground hay, bags of sawdust or clay are used for packing behind the sheathing, and are useful also for dealing with an incipient blow. Fires may break out in the timbering or in the packing and it is necessary to be ready to drill holes through the skin of the shield so that water may be forced through to extinguish such fires.

74. Loading Equipment.—To load the excavated material into the cars, hand shovels are generally used. In some cases belt conveyors have been used with marked success. See Fig. 92. So many improvements are now being made in car loading machinery for mining use that it is worth while, for any shield driven tunnel project, to investigate these devices rather than to rely wholly on precedent, because the time spent in loading the muck into the cars represents an important fraction of the total time used in building a tunnel.

J. THE WORKING PLATFORM

75. Purpose of Platform.—When the size of the tunnel is small the whole interior surface may be reached from the working floor level, or a plank or two laid across the tunnel may make a platform high enough to reach the roof to erect the upper segments of the lining, tighten bolts, do grouting and other work. When the diameter of the tunnel is usually about 15 ft. or more a movable platform will be found more economical for doing such work. It is customary, then to build a substantial staging or platform which runs on tracks laid along the sides of the tunnel. This platform is attached to the shield and is dragged forward as the shield advances.

76. Construction of Platform.—The platform, generally of wood, should be simple and substantial in design. The use of steel for the frame of the platform would reduce the fire hazard and also the obstruction as the members would be smaller. At the Rotherhithe Tunnel (E-17) a steel platform was used. It may have one or more decks according to the size of the tunnel. In cast iron lined tunnels the track for the platform is conveniently supported on brackets attached to the circumferential flanges of the lining. Usually the rails are attached to these brackets, but a successful construction has been obtained by having the brackets carry rollers on which run inverted rails connected to the platform.

77. Example, Blackwall Tunnel Platform.—Brunel's Thames Tunnel appears to have had some kind of traveling platform. Perhaps the first iron-lined shield driven tunnel of the modern type to be equipped with a traveling platform was the Blackwall tunnel in 1892 (E-7). The inside diameter of this tunnel was 25 ft. The platform, occupied practically the whole width of the tunnel; it had three decks and was 40 ft. long. It traveled on rails supported on brackets attached to the iron lining.

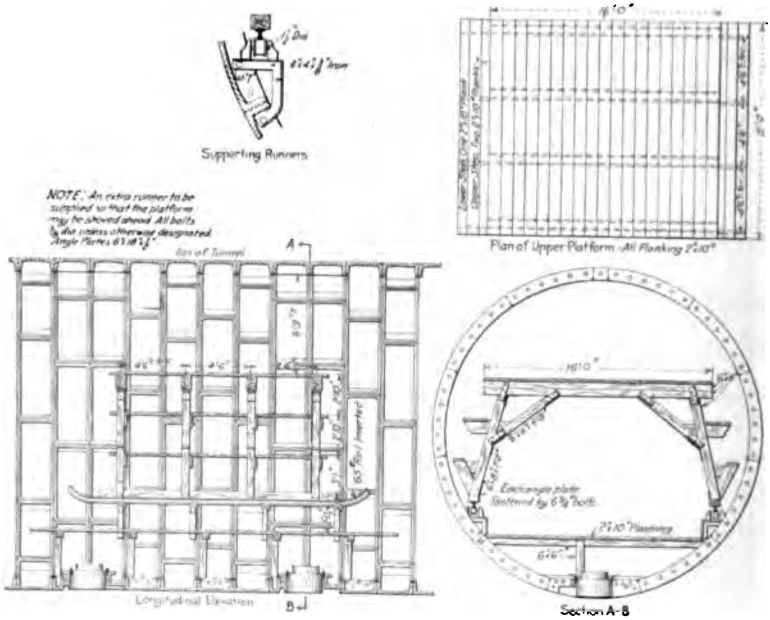
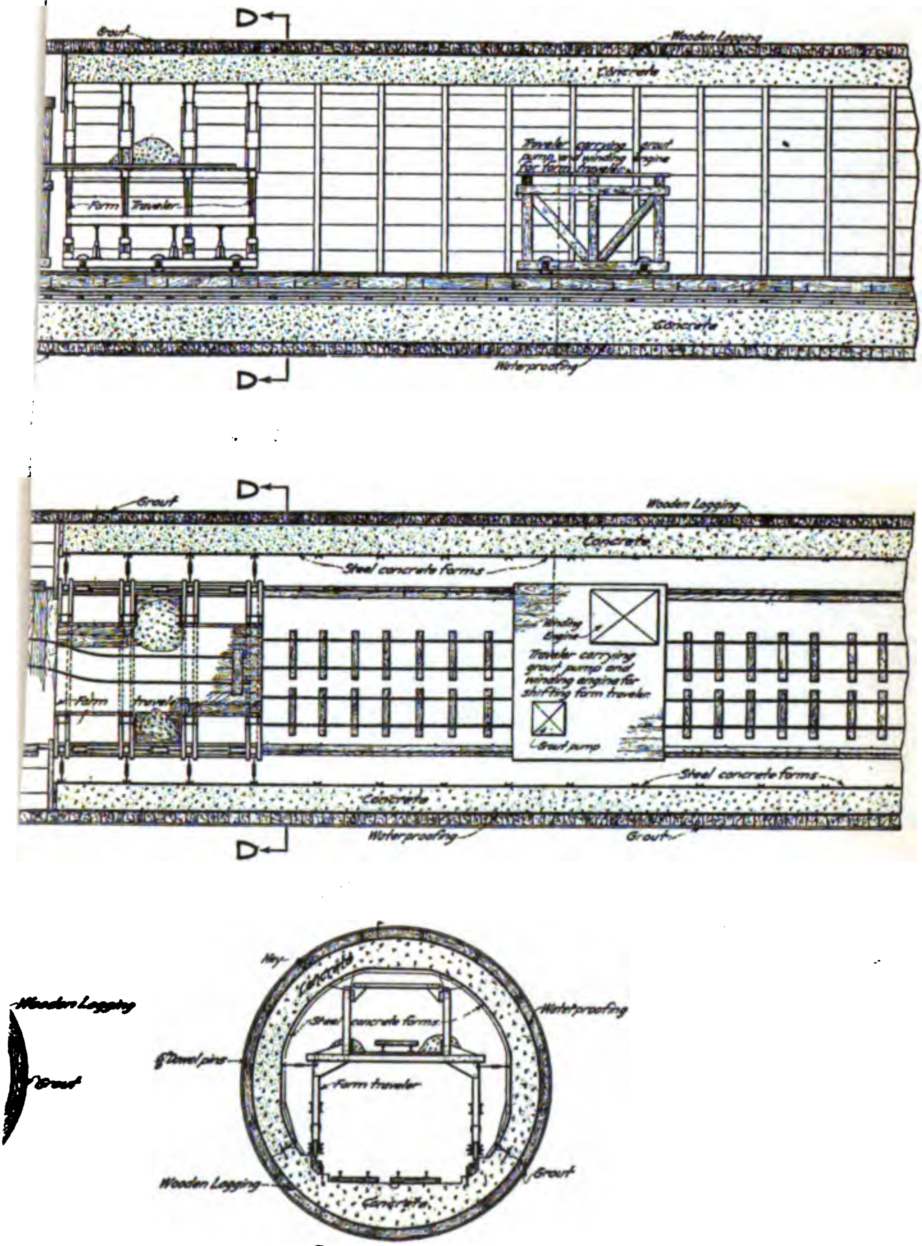


FIG. 91.—Working platform. Pennsylvania Railroad tunnels (A-18). (From *Eng. News.*, Dec. 13, 1906.)

78. Example, Pennsylvania Railroad Hudson River Tunnels.—On the Hudson River tunnels of the Pennsylvania Railroad the platforms were 15 ft. in length and are shown in Fig. 91. The top deck was 16 ft. wide. The two bracket platforms which project on each side were termed "bolting platforms" and were used by the men tightening up the bolts. The rollers were attached to the lining while the rails (inverted 65-lb. rails), were fastened to the platform. These platforms were found to be efficient and caused no obstruction.

79. Example, Dorchester Tunnel.—The lining of the Dorchester tunnel (A-34) consists of a wooden primary lining and an



SECTION D-D

SHOWING COMPLETED TUNNEL WITH
STEEL FORM AND FORM TRAVELER IN PLACE.

internal concrete lining. The traveling stage used in this tunnel is shown in Fig. 92. It is described as follows in the twenty-second annual report of the Boston Transit Commission. "A belt conveyor about 110 ft. long is attached to the rear of each shield and is pulled along as the shield advances. It runs on two narrow gauge working tracks which are laid on the invert of the tunnel as fast as the latter is put in place. The belt conveyors serve to convey the excavated earth past the points where the operations of placing the wooden lining, waterproofing, invert concrete and grouting outside the wooden lining are going on and so avoid interference with them. The earth is discharged from the conveyors into muck cars, which are pushed, one at a time, under the discharge chutes about 100 ft. in the rear of the shields . . . Concrete is brought into the tunnels in steel cars containing about one cubic yard and is hoisted by means of elevators to overhead platforms before being shoveled into the forms. There are two of these concrete elevators at the heading of each tunnel. The forward ones for invert concrete are just behind the shields and hoist concrete cars from the construction tracks alongside the belt conveyors. The rear ones which are used for arch concrete are just behind the belt conveyors and hoist the concrete cars from the same track that the conveyors run on . . . The elevators and overhead platforms span the construction tracks and the belt conveyor, and travel on two rails which are supported on the lower concrete duct line benches along the sides of the tunnel . . ."

K. BOLTING EQUIPMENT

80. Hand Equipment.—The equipment for tightening bolts of a cast iron lined tunnel consists of bolt wrenches and drift pins (called "bodgers" by the English tunnel men). Wrenches of ordinary lengths are used for the initial erection. For tightening up the bolts after the shield has passed on it is well to provide a piece of pipe to slip over the handle of the wrench so as to increase the purchase. The most suitable length of handle for a given bolt diameter is perhaps best determined by some tests in each instance. For bolts having a diameter of 1½ in. a handle about 3 ft. long has been found suitable.

81. Mechanical Bolting Equipment Desirable.—Tightening up the bolts in a cast iron lined tunnel is no small part of the total

work. For example, on the Hudson River tunnels of the Pennsylvania Railroad (A-18) there were approximately 640,000 bolts. Each of these had to be put in at the time of initial erection. Then each bolt was tightened up as the pressure of the shield and the working of the joints loosened them. Then each bolt had to be taken out to be grummeted, was replaced and tightened again. Those that leaked after this operation were replaced and retightened. In fact, each bolt had at least three tightenings and one removal, or four screwing operations, performed on it. Consequently, on this portion of the Pennsylvania tunnels alone about 2,500,000 nut-screwing operations took place. It seems reasonable that some nut-screwing device might be designed, operated by compressed air or electric energy, that would be portable enough for one or two men to handle and so constructed that it would work in the rather narrow confines of the flanges, which would do the work at an increased speed and result in less labor cost. A ratchet wrench, even, might be better than an ordinary bolt wrench.

L. GROUTING PLANT AND EQUIPMENT

82. The Greathead Grouting Pan.—The grouting pan as used now for forcing grout outside of the tunnel lining has a close resemblance to that devised in 1886 by Greathead and used first on the construction of the City and South London Railway. It is described by Greathead (*Proc. Inst. C. E.*, vol. 123, p. 63) as follows. "A cylindrical vessel, capable of withstanding a pressure of 70 or 80 lb. per square inch, has through its axis a shaft or spindle working in a stuffing box at each end of the vessel, and provided at one or each end with a handle outside, and carrying, inside the vessel, a number of paddles. The lime and water are introduced through an opening at the top, having a lid capable of being closed air-tight; and the mixture is discharged by compressed air through a length of flexible hose pipe ending in a branch or nozzle, the nozzle being inserted in holes in the tunnel lining provided for the purpose. The smaller grouting pans are usually worked by two men; one continually keeps the paddles revolving and opens and closes the air and discharge valves, while the other has charge of the branch at the end of the hose . . ."

83. Later Changes in Details.—The paddles of the modern grouting pan are turned by compressed air engines instead of by hand. The hinged door at the top, instead of lifting up to open as in the original Greathead pattern, now is made to flop down to open and to lift up to shut. By this means, when the door is lifted after charging, and the air turned on, the air pressure forces the door tight against its seating and thus does away with the screwing up of the door formerly necessary.

84. Size of Grouting Pan.—The dimensions of an ordinary grouting pan are about 3 ft. long and 21 in. in diameter. The air supply is a one-inch pipe and the grout discharge is a 1½ in. pipe (Fig. 93).

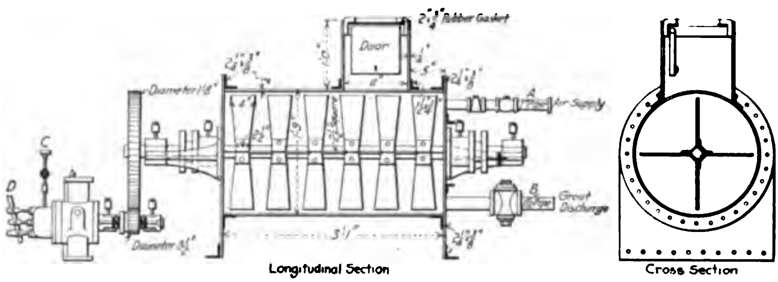


FIG. 93.—Greathead type of grouting machine driven by compressed air engine.

85. Nipple and Valve.—It has been found more convenient not to screw the grout pipe nozzle directly into the grout hole but to interpose a nipple and valve between the segment and the grout pipe so that, when the space is filled with grout, the valve can be closed until the grout has set. Otherwise it is necessary to remove the grout pipe and to put in the plug while the grout is still liquid. This results in loss of grout in all holes above the horizontal axis.

86. Mounting of Grouting Pan.—For portability the machine is mounted on skids, or better still, on flat cars which can run on the tunnel tracks.

87. Other Types of Grouting Machines.—Grouting machines of several different patterns have been made. Some have the cylinder vertical instead of horizontal. In others the grout is mixed and agitated by jets of compressed air instead of by paddles. These machines give good service and there is probably little to choose between them and those of the Greathead type as a practical tool.

88. Grout Pump.—For some work in France a grout pump was designed. The object was to make the grouting operation continuous instead of intermittent as with a grouting pan. One of these machines was tried at the Astoria Gas tunnel at New York, but the result was not good. There is a field open, however, for development along these lines.

M. AIR BULKHEADS AND AIR LOCKS

89. Purpose of Air Bulkheads.—The purpose of the air bulkheads is to form the enclosures of the air chambers in tunnels driven under compressed air. The bulkhead must be air tight and capable of carrying the pressure of the compressed air, and it must be provided with means for passing through it the various facilities needed for carrying out the work in the tunnel as well as means for the passage of men and materials.

90. Specifications for Bulkhead Wall.—It is becoming customary in tunnel contracts to specify definite requirements as to the design of the bulkhead wall so that there may be no dispute between the engineer and the contractor as to what shall be deemed to constitute a proper construction. The following clauses taken from the standard specifications of the Public Service Commission of the First District of New York State for tunnels in connection with the subways in New York City (1914–1916) may be considered as representing modern practice in this matter.

"Air chambers shall be formed in the tunnels by bulkheads of concrete or brick laid in Portland cement mortar or of steel plate diaphragm construction according to an approved design. The bulkheads and air locks shall be of sufficient strength to sustain safely a pressure of 50 lb. per square inch. Whenever the air pressure in the heading exceeds 22 lb. per square inch above atmospheric pressure, two air chambers shall always be in use, excepting when headings are being started from shafts for such time as may be necessary, and the pressure in the outer one shall not exceed one-half the pressure in the heading. The distance from the heading to the nearest bulkhead shall not exceed 800 ft. during the progress of the work."

91. Materials of Construction.—All the early bulkheads were of brick. This was because concrete in those days had not come into the universal use it later attained. Concrete has the great advantage of being placed in a plastic state so that it flows closely around the air locks and pipes that are built into the wall. A

bulkhead of brickwork has, on the other hand, the advantage of being more readily removed when the work is completed, but the labor of erection is more expensive. Bulkheads of steel have been used and have given great satisfaction.

92. Masonry Bulkheads.—In a masonry bulkhead wall it is usual to build in grout pipes and to give the wall, especially at the top, a good grouting in order to seal it closely to the lining. The face of the wall toward the air pressure may be plastered over with Portland cement mortar in order to render it still more air tight. The principal objection to the use of masonry bulkheads is that when the compressed air work is over and the walls are to be removed, this must be done carefully so as to avoid damage and even risk of damage to the tunnel lining. This is slow and laborious work.

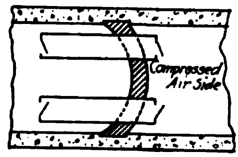


Fig. 94.—Domed brick air bulkhead at East Boston Tunnel.

93. Dome Shaped Masonry Bulkhead. In the construction of the East Boston tunnel a (A-13) dome shaped bulkhead, as shown in Fig. 94 was built of brickwork. By this means the thickness of the wall in this tunnel, the largest inside dimension of which was 23 ft. 4 in., was only 3 ft. The brickwork was keyed into the masonry lining of the tunnel and was strengthened with iron hoops.

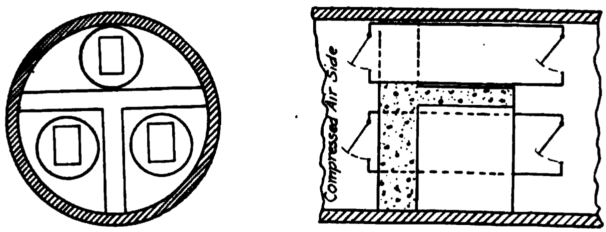


Fig. 95.—Buttressed air-lock bulkhead wall.

94. Buttressed Bulkhead Wall.—It is possible to reduce the thickness of the wall by means of vertical and horizontal buttresses as shown in Fig. 95. By this design the thickness of the concrete is greatly reduced, especially where it butts against the tunnel lining which is where its removal is most difficult. Instead of buttressing the wall with masonry, it would be equally possible to support it by means of a steel construction.

95. Thickness of Existing Masonry Bulkheads.—In order to show the general practice with respect to the thickness of masonry bulkhead walls, the following Table XIV is given.

96. Determination of Thickness.—The thickness of a bulkhead wall may be calculated. Owing to its great thickness as compared with its span it is most probable that it will act as an arch or a dome, and the best method is to consider so in the computations, giving proper consideration to the large openings caused by the locks. The value of the calculations is likely to be of theoretical interest only, however, and a more satisfactory expression may be had by a consideration of the data as given in Table XIV. Although several of the smaller tunnels indicate a greater ratio, it would appear that a ratio of from 0.4 to 0.5 between the thickness of the wall and the inside diameter

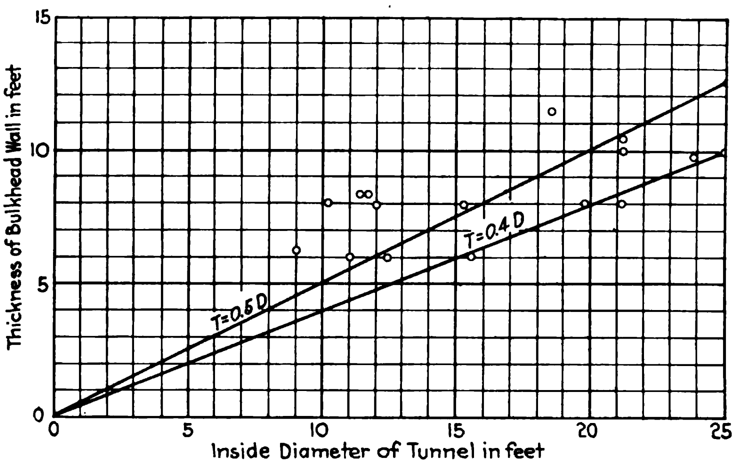


FIG. 96.—Relationship between diameter of tunnel and thickness of concrete bulkhead walls.

of the tunnel would be suitable. Due consideration, should be given, however, to the air pressure to which the wall may be subjected.

97. Diagram of Thickness of Concrete Bulkheads.—In Fig. 96 the curves

$$T = 0.4D \tag{42}$$

and

$$T = 0.5D \tag{43}$$

are plotted. These represent the relation between the thickness T of the bulkhead wall and the internal diameter D of the tunnel.

TABLE XIV.—THICKNESS OF MASONRY BULKHEADS USED IN THE CONSTRUCTION OF TUNNELS

Reference No.	Tunnel	Internal diameter, D, feet	Approximate date	Maximum air pressure, above atmosphere, lb. per sq. in.	Thickness of wall, T, feet	Ratio, $\frac{T}{D}$	Material
(E-4)	Mersey	9.00	1888	27	6.25	0.69	brick
(A-5)	Sarnia	19.83	1888	28	8.00	0.40	brick
(S-2)	Glasgow District	11.00	1891	23	6.00	0.54	brick
(E-7)	Blackwall	25.00	1892	35	12.50	0.50	brick & concrete
(A-8)	Ravenswood	10.16	1893	48	8.00	0.79	brick
(E-8)	Waterloo & City	12.42	1893	..	6.00	0.48	brick
(E-15)	Baker St. & Waterloo	12.00	1898	32	8.00	0.67	brick
(E-11)	Greenwich	11.75	1899	26	8.25	0.70	brick
(E-13)	Lea	11.50	1901	15	8.25	0.72	brick
(A-16)	Battery	15.46	1901	..	6.00	0.39	brick & concrete
(A-19)	P. R. R. East River	21.16	1905	37	10.50	0.50	concrete
(A-18)	P. R. R. Hudson River	21.16	1905	37	10.00	0.47	concrete
(A-18)	P. R. R. Hudson River	21.16	1905	26	8.00	0.38	concrete
(G-4)	Elbe	18.50	1907	..	11.50	0.62	
(F-12)	Concorde Metropolitan	23.94	1909	..	9.85	0.41	concrete
(A-17)	Hudson & Manhattan	15.25	1905	40	8.00	0.52	concrete
(A-27)	Old Slip East River	16.00	1914	38	9.50	0.59	concrete
(A-28)	Whitehall East River	16.50	1914	35	9.50	0.57	concrete
(A-30)	14th Street East River	16.50	1916	40	8.00	0.48	concrete
(A-35)	60th Street East River	16.50	1916	48	8.00	0.48	concrete

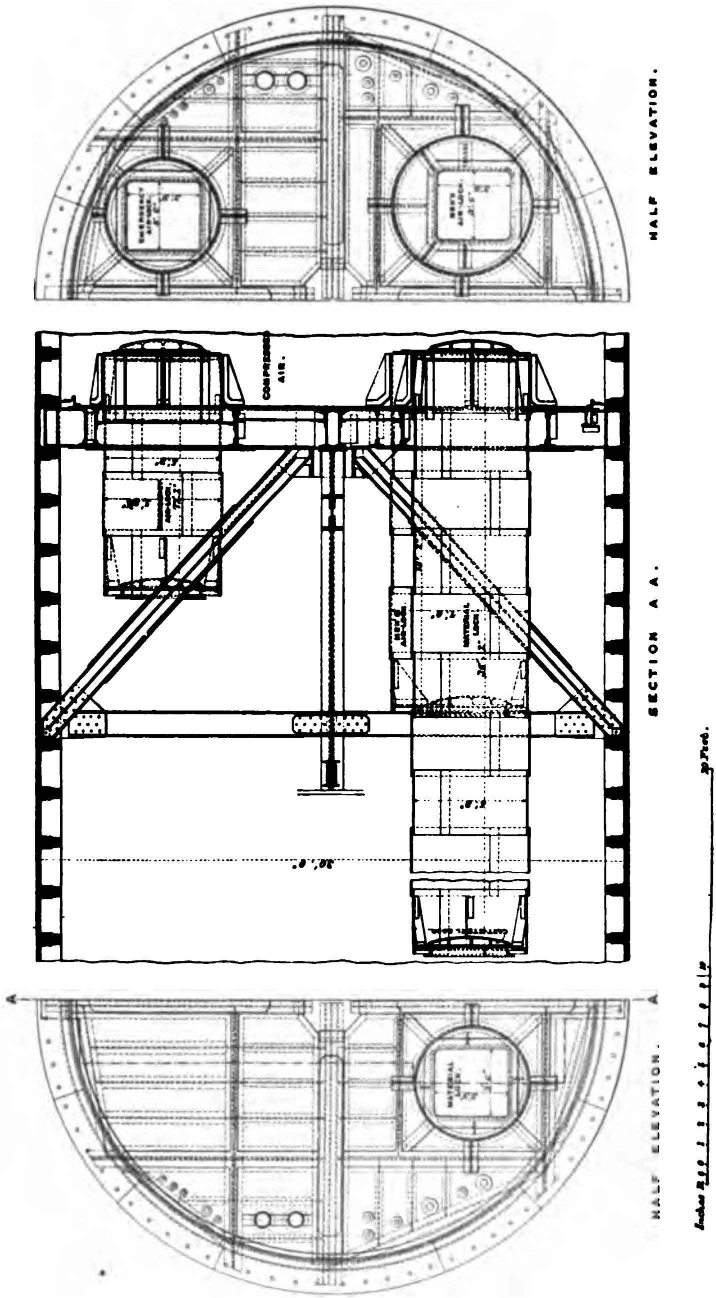


FIG. 97.—Structural steel bulkhead wall. Rotherhithe Tunnel (E-17). (From *Proc. Inst. C. E.*, vol. 175)

For comparison the ratios for tunnels previously built (as shown in Table XIV) are also plotted on the diagram.

98. Steel Bulkheads.—Steel bulkheads have several important advantages over those made of concrete or brickwork. Their proper dimensions can be computed with greater certainty. Their erection is simple and their removal can be accomplished without fear of danger to the tunnel. Their cost may be less. Experience has shown that they can be made air tight. It is to be expected that in the future steel bulkheads will be more generally used.

99. Example, Rotherhithe Tunnel.—In *Proc. Inst. C. E.*, vol. 175, pp. 197–198, the steel bulkhead used on the Rotherhithe tunnel (E-17) is described as follows. "The bulkhead (shown in Fig. 97) consisted of a diaphragm of 5/8 in. steel plating supported by rolled joists and built up beams crossing each other. The load on these was taken by four main girders, 2 ft. deep, radiating from the center. Each of these girders took a bearing on one of the flanges of the iron lining at its outer end, while at the center the combined load from all four girders was transmitted to the tunnel behind by four steel struts which extended diagonally, two in a vertical and two in a horizontal direction, to the iron lining. The air pressure for which the bulkheads were designed was 35 lb. per square inch, the total load on the structure being over 1,500 tons (3,360,000 lb.). The skin plating of the diaphragm was bolted round its outer edge to a ring of 3/8-in. plates which had been inserted between two rings of segments at the time the lining was erected. The ring of plates projected about 4 in. inside of the inner edges of the cast iron flanges of the two rings. . . . The greater portion of the length of the air lock was arranged to be on the atmospheric side of the bulkhead, so as to put as much as possible of the material of the locks in tension."

100. Air Locks.—The air locks form the means of access for men and materials to and from the air chamber. A simple door in the bulkhead would not serve this purpose, because great force would be needed to open it, and when opened, the compressed air in the air chamber would escape uncontrolled in such quantities as to make the maintenance of the proper pressure impossible. An air lock, therefore, is provided. See Fig. 98. This is a chamber having a door at each end, both doors swinging in the direction of the air pressure. One of the two doors always

is held tightly shut by the difference in the air pressure on its two faces, and when the lock is being used for transit, both doors are shut. Let it be assumed that the door nearest the air chamber is shut and that it is desired to enter into the air chamber. The air pressure in the lock is normal so that the door at the normal

FIG. 98.—An air lock. The angles riveted on the outside are to anchor the lock in the masonry bulkhead. (*Ravenswood Tunnel*, A-8.)

air side is readily opened for entering into the lock. When in the lock the door is closed and a valve opened, which lets the compressed air into the lock and the door is soon forced tight against its jamb by the rising air pressure in the lock, thus preventing the escape of the air. The inflow of the compressed air is continued until the pressure in the lock is equalized with that in the working air chamber, when the inner door is readily opened and passage through the air lock effected. It will be seen that for each passage only a lock full of compressed air is wasted. Returning from the air chamber the operation of the lock is reversed, but is, in principle, the same.

101. Air Locks in Small Tunnels.—In small tunnels it has been usual to put in only one lock which serves then for the passage of both men and materials. Whenever the tunnel is large enough, however, for more than one lock, there should be pro-

vided at least an emergency lock also. The Rotherhithe pilot tunnel had an internal diameter of 11.67 ft. and there was found room for two locks, proving that even in comparatively small tunnels more than one lock may be provided.

102. Tunnels with Single Air Lock.—Table XV gives particulars of the size of air locks in tunnels which have been constructed with only one lock in the bulkhead wall.

TABLE XV.—TUNNELS WITH SINGLE AIR LOCK

Ref. No.	Tunnel	Internal diam. of tunnel, feet	Size of air lock: Diameter, feet	Length, feet	Volume, cubic feet	Remarks
(E-10)	City & South London..	10.50	3.75×5.00	12.00	225	rectangular
(S-1)	Glasgow Harbor........	16.00	4.25×5.58	13.00	309	rectangular
(S-2)	Glasgow District.......	11.00	5.75	13.00	340	
(A-8)	Ravenswood...........	10.16	6.00	10.00	283	
(E-8)	Waterloo & City.......	12.12	5.75	13.00	338	
(E-15)	Baker St. & Waterloo .	12.00	5.75	13.50	350	
(E-13)	Lea..................	11.50	5.83	17.50	465	

103. Classification of Air Locks.—When more than one lock is provided they are classified as follows:

(a) Material locks.
(b) Men locks.
(c) Emergency locks.

The material locks are used for taking materials into and out of the tunnel and are provided with air valves of large size, usually 4 in., giving quick transit. The men locks are used for the passage of the men working at the face and are furnished with valves regulated to make the time of transit safe (see Chap. XVII). The emergency locks are used for the escape of the men working in the air chamber in case the tunnel is flooded.

104. Material Lock.—The material lock should be as long as the outside diameter of the tunnel plus a margin of 2 or 3 ft. to allow the longest timber that might be required at the heading being passed through the lock. This would be the minimum requirement in a small tunnel, because usually the length should be enough to allow three or four cars to pass through at one time. It must be remembered that one door must have room to swing inward.

105. Timber Locks.—In some cases "timber locks," or "pipe locks" consisting of a length of pipe from 10 to 21 in. in diameter, is provided to take care of the long timbers and the pipes, but it is usually easier to send them straight through a lock on a flat car, if the lock is long enough, without the rehandling necessary with a timber lock.

106. Size of Material Lock.—The diameter of the material lock will depend to a degree on the dimensions of the cars used for transportation, but 5.75 ft. may be considered a minimum and 6 to 7 ft. an average. Modern practice seems to lean to 7 ft., where the tunnel is large enough.

107. Men Lock.—While in the material lock the air valves should be of a diameter of about 4 in. so that no time is lost in locking in and out the materials, this is different in the men lock. In Chap. XVII some account will be found as to the reasons why the rate at which men should be decompressed must be strictly limited. With one lock serving for men and materials it is most difficult to ensure that men wanting to come out quickly, will not let themselves out on the muck tap, or large valve. This will lead surely to sickness and death.

108. Size of Men Lock.—Wherever possible the lock should be of ample cross-section so that the men can stand upright without knocking their heads, and so that a bench may be placed along one or both sides with room for the whole crew to sit comfortably while going in and particularly during the slow process of coming out. The man lock should be not less than 6 ft. in diameter and a 7-ft. diameter is desirable when the size of the tunnel permits.

109. Length of Men Lock.—The length of the men lock is determined by the number of men in the compressed air gang. In Chap. XV is a discussion of the number of men who may be expected to be at work in tunnels of various sizes. Allowing 15 in. of bench length per man an idea is gained of the total length of bench which should be provided to take care of the entire gang. Table XVI shows the bench length needed according to this estimate. An allowance of 3 ft. is made for the space occupied by the door when it opens into the lock and for the man who operates the valve.

In a lock of a diameter of 6 to 7 ft. there would be room for two benches, so that the length of the lock would be about one-half of that given in the table.

TABLE XVI.—BENCH LENGTH IN MEN LOCK

Diameter of tunnel in feet	5	10	15	20	25	30	35
Number of men in shift minimum. Feet	5	9	15	24	35	49	65
Bench length in lock, minimum	9	14	23	34	48	64	85
Bench length in lock, maximum. Feet	13	21	32	48	69	94	125

110. Size of Air Pipe.—The air pipe on the men lock should be 1 in. in diameter. The decompressing valve may be of an automatic, constant rate type. For further check on the rate of decompression, the lock should be provided with a clock and a pressure gauge.

111. Heating of Men Lock.—It would be useful to have some means of heating the men lock during the decompression period, when the lowered pressure results in cold and fog. This is a temptation to the sweat soaked men to hurry a process which must not be hurried. It could be done readily with steam or hot water radiators or with electric heaters.

112. Cleaning of Men Lock.—Above all things the men lock should be kept clean and tidy. An occasional coat of paint should be applied. The floor should be of concrete and the space below the bench should be filled up solid to prevent accumulation of paper and dirt. The lock should be well lit.

113. Emergency Lock.—The emergency lock is provided as a means of escape for the men in the air chamber of the tunnel in a crisis when a blow at the face is filling the tunnel with water and ground. The lock is set as high as possible in the tunnel, because this part of the tunnel is the last to be filled. When the tunnel is large enough a runway for the men is provided along its upper part. This runway leads directly to a platform at the door of the emergency lock. During the construction of the tunnel under air pressure this lock is always kept "open to the air," which means that the door on the compressed air side is always open. Thus, when the men must flee, the lock is open for them and when the last man is in the lock the door is closed and the gang may be locked through safely to the normal air. This lock should be kept lit.

114. Specifications for Emergency Lock.—The provision of an emergency lock is now often required in the specifications as follows. (*New York Transit Commission.*)

"The emergency lock shall be located as high up in the bulkhead as practicable, shall not be less than 5 ft. in diameter and shall be large

enough to hold an entire heading shift. When not occupied the emergency lock shall be kept open toward the heading and shall be ready for instant use at all times."

115. Size of Emergency Lock.—Frequently the cross-section of the emergency lock is restricted on account of the desire to place the lock as high up in the bulkhead as possible, but as a small door may be put in a large lock, it seems that, unless the space available in the bulkhead limits the size, the emergency lock might be made of the same size as the men lock, or from 6 to 7 ft. in diameter. It might then be necessary to place a step at the entrance to the lock at the compressed air end, but it is probable that a wider lock would not be choked as readily as a smaller one and would allow the crew to get to safety more rapidly.

116. Length of Emergency Lock.—Under no circumstances should there be a question as to this lock being large enough to hold the entire gang, including engineers, inspectors and other people that might be in the tunnel, and for this reason the length should be estimated according to the extreme number rather than the average and at the change of shift. Do not trouble to provide seats in this lock.

117. Particulars of Air Locks Used in Tunnels.—Table XVII gives particulars of air locks which have been provided in the bulkheads of tunnels having more than one lock in the bulkhead and about which information has been obtained. In tunnels where the same lock was used for material and men, the dimensions are shown under material lock.

118. Engineer's Lock.—On some tunnels a special lock has been provided for the engineers to use in carrying the lines and levels from the outside into the compressed air chamber. On the Sarnia tunnel (A-5) an engineer's lock was furnished, consisting of a 12-in. pipe in which were set at each end crosshairs similar to those in a transit. On the East River tunnels of the Pennsylvania Railroad (A-19) a transit lock was provided consisting of a 30 ft. length of 12-in. pipe with an enlargement about 2 ft. by 2 ft. on the normal air side for taking the transit. As the pipe cantilevered 17 ft. beyond the bulkhead wall on the one side and 3 ft. on the other it was necessary to have the pipe firmly braced and stayed to prevent movement during reversal of air pressure.

119. Necessity for Engineer's Lock.—When no special lock is provided the survey corps is forced to use one of the regular locks. If the men or material lock is used it delays the progress

TABLE XVII.—AIR LOCKS IN TUNNELS WITH MORE THAN ONE LOCK IN BULKHEAD

Ref. No.	Tunnel	Internal diameter of tunnel in feet	Material lock			Men lock			Emergency lock			Date
			Length, ft.	Diameter, ft.	Volume, cu. ft.	Length, ft.	Diameter, ft.	Volume, cu. ft.	Length, ft.	Diameter, ft.	Volume, cu. ft.	
(A-5)	Sarnia	19.83	17.0	6.00	480	17.0	6.00	480	*A*	*A*	*A*	1888
(E-7)	Blackwall	25.00	16.0	7.00	615	16.0	7.00	615	10.5	5.00	205	1892
(E-11)	Greenwich	11.75	17.0	7.00	655	*A*	*A*	*A*	17.0	4.5×3.3	200	1899
(A-13)	Boston Harbor	{20.54 23.33}	27.0	6.00	765	27.0	6.00	765	27.0	6.00	765	1899
(E-17)	Rotherhithe	27.67	36.0	5.75	935	18.0	7.00	695	12.0	5.75	310	1904
	Rotherhithe, pilot	11.67	*B*	5.75	*B*	*A*	*A*	*A*	*B*	4.7×3.5	*B*	1904
(A-19)	P. R. R., East River	21.16	24.0	7.00	925	20.0	7.00	770	24.0	7.00	925	1905
(A-18)	P. R. R., Hudson River	21.16	25.0	7.00	965	10.0	6.0×5.0	260	20.0	4.0×3.0	180	1905
(G-4)	Elbe	17.71	22.0	5.4	504	29.0	6.1	847	*A*	*A*	*A*	1907
(F-12)	Concorde Metropolitain	23.97	24.5	7.0	945	11.5	6.0	310	20.0	4.00	250	1908
(A-34)	Dorchester	18.67	50.0	7.5	4,418	30.0	6.0	849	*B*	*B*	*B*	1915
(A-27)	Old Slip	16.00	26.5	6.5	880	26.5	6.5	880	20.0	3.5×4.66	251	1914
(A-28)	Whitehall	16.50	26.5	6.5	880	26.5	6.5	880	20.0	3.5×4.66	251	1914
(A-30)	14th Street	16.50	26.0	8.5	1,474	19.25	6.5	639	20.0	3.5×4.66	251	1916
(A-35)	60th Street	16.50	40.0	7.5	1,768	20.0	6.0	566	20.0	6.0	566	1916

Note *A* means *not used*.
Note *B* means *not known*.

of construction. Frequently, therefore, the emergency lock is used for survey purposes. This may result in the door being closed against the men at the face when they need to use the lock. An engineer's lock is particularly necessary in tunnels driven through soft silt. These tunnels undergo constant change of shape and position during the construction period and frequent survey through the lock is, consequently, necessary.

120. Suggested Arrangement of Engineer's Lock.—It is suggested that an efficient engineer's lock which will not interfere with the proper use of the usual locks, which will not occupy

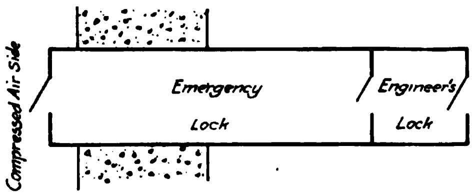


FIG. 99.—Suggested extension to the emergency lock to allow its use for surveys without interfering with its emergency use.

additional space in the bulkhead wall and which may be provided at a reasonable cost may be attained in the following manner. If an extension is added to the emergency lock (Fig. 99) about 6 ft. long and furnished with a door, so that the emergency lock will have three doors, the work of the surveyors may be carried out in this extension without at any time closing the emergency lock at the compressed air side.

121. Survey Plugs in Air Locks.—It is found that the monuments, scales, or benchmarks used in the survey in the air locks should be attached to the masonry of the wall rather than to the metal of the lock, as this shifts slightly under the reversal of air pressure and with changes in temperature.

122. Construction of Locks.—In a few cases, especially in the early days, where the diameter of the tunnel has been small the air lock has consisted of a horizontal hole in the bulkhead wall, which was made thick enough to provide a lock of sufficient length. At each end was a door, the frame of which was set in the masonry. Usually, however, the lock consists of a horizontal cylinder fabricated of steel plates and calked for air tightness as a boiler shell. At each end is a door, hinged at the side and swinging to open toward the compressed air side of the tunnel. One of the doors, therefore, opens into the lock while the other

TABLE XVIII.—DIMENSIONS OF DOOR OPENINGS IN AIR LOCKS

Ref. No.	Tunnel	Material lock		Men lock		Emergency lock	
		Height, ft.	Width, ft.	Height, ft.	Width, ft.	Height, ft.	Width, ft.
(E-10)	City & South London	4.00	3.00	*A*	*A*	*A*	*A*
(E-4)	Mersey	4.00	3.00	*A*	*A*	*A*	*A*
(S-1)	Glasgow Harbor	5.58	4.16	*A*	*A*	*A*	*A*
(S-2)	Glasgow District	4.00	3.00	*A*	*A*	*A*	*A*
(E-7)	Blackwall	5.00	4.00	5.00	4.00	3.50	2.00
(F-1)	Clichy Siphon	4.40	3.60	*A*	*A*	*A*	*A*
(A-8)	Ravenswood	3.67	3.16	*A*	*A*	*A*	*A*
(E-8)	Waterloo & City	4.00	3.00	*A*	*A*	*A*	*A*
(E-11)	Greenwich	5.00	4.00	....	*A*	1.75	3.50
(E-13)	Lea	3.75	3.00	*A*	*A*	*A*	*A*
(E-17)	Rotherhithe	3.75	3.50	3.75	3.50	3.75	3.50
(E-17)	Rotherhithe, pilot	4.00	3.50	....	....	3.50	1.67
(A-19)	P. R. R. East River	5.00	4.00	5.00	4.00	5.00	4.00
(A-18)	P. R. R. Hudson River	5.33	4.00	4.50	2.67	2.83	1.75
(F-12)	Concorde Metropolitain	5.00	4.00	4.75	2.75	3.50	2.50
(A-27)	Old Slip	4.66	4.08	4.66	4.08	3.33	2.00
(A-28)	Whitehall	4.66	4.08	4.66	4.08	3.33	2.00
(A-30)	14th Street	4.7 & 5.7	4.0 & 5.5	4.66	4.08	3.33	2.00
(A-35)	60th Street	5.25	4.00	4.00	3.25	4.00	3.25

Note *A* means *not used.*

opens out of the lock. The flat surface of the door strikes against the door frame and is provided with a strip of rubber to make a tight joint. The doors are furnished with hand grips so that they may be swung open and closed and held tight against the frame until the air pressure is sufficient to hold them shut. No catch is provided on the doors. The floor in the locks should be made of solid concrete. In the material locks tracks for the cars used for transport of materials must be laid. As the cylinder is better capable of withstanding internal than external pressures, the lock is set in the bulkhead wall so that it extends but slightly into the compressed air chamber of the tunnel. It is well to remember that after the first bulkhead is built the air locks for the succeeding bulkheads cannot be passed through the air locks in one piece. It is necessary, therefore, either to assemble them in the tunnel under air pressure or better to store them in advance of the bulkhead before it is built. Figure 98 shows an air lock before being installed.

123. Lock Doors.—Table XVIII shows the dimensions of the door openings of several tunnel locks of which the figures are available.

124. Size of Door, Material Lock.—The door opening of the material lock should be as large as the size of the lock will permit. In a 7-ft. diameter lock a door opening 5 ft. high and 4 ft. wide can be provided. An opening of that size will speed the work of passing through the cars, because it will permit, for usual car sizes and car loadings, a man to pass by and arrange the cars in the lock. For a lock 6 ft. in diameter an opening 4 ft. 7 in. high and 3 ft. 6 in. wide can be provided. Smaller size material locks should not be used unless the tunnel is so small that this cannot be avoided.

125. Size of Door, Men Lock.—An opening wider than from 30 to 32 in. is unnecessary in the men lock. This is the width of an ordinary door in a house and a man lying on a stretcher may be carried through a door of that width. On the other hand, for the greater comfort of the men the height of the door should be made as great as the conditions will permit. In a 7-ft. diameter lock the door height may be about 5 ft. 6 in. and in a 6-ft. diameter lock about 4 ft. 6 in.

126. Size of Door, Emergency Lock.—As before stated the emergency lock should be placed as high as possible in the tunnel. This applies rather to the height of the bottom of the door

(*Photo by P. P. Pullis.*)

FIG. 100.—An air-lock bulkhead wall. The pressure side. Emergency lock at top. Pipe lock in middle. Man and material locks below. Air, water, electric, cable and other pipes shown. (Courtesy of *New York Transit Commission.*)

opening, however, than to the level of the floor of the lock. The width of the door should be about 30 in. If the bottom edge of the door opening is set 15 in. above the platform in front of the opening at the compressed air side and the floor of the lock is at the same level as the platform, then it will be found usually that with a door height of from 36 to 39 in. easy access will be provided to the lock. At the other end of the lock the door may reach all the way down to the floor level. The difference in level between the emergency platform and the door sill should be made by a ramp rather than by steps.

127. Fitting of Air Locks.—On every air door there should be a glass bullseye, about 6 in. in diameter so that the lock tender can observe what is happening in the lock. All locks, including the material lock, should be fitted with man valves of 1 to 1½ in. in diameter for air inlet and outlet, as there may come times when the men will have to use the material lock for passage. The emergency lock should have a 1½-in. emergency cock which can be opened from the compressed air chamber of the tunnel, so as to "bring back" the lock in case of necessity. For locking in and out materials, 4-in. diameter pipes and valves are suitable. The material locks should be fitted with shut-off valves on these 4-in. lines, so that the men using the lock may use the man valve. Figure 100 shows the high pressure face of a bulkhead and Figure 101 shows the low pressure face of another.

128. Bridge Track.—At the doors of the material lock it is necessary to use short lengths of movable tracks spanning over the gap or well in which the lock door swings. This may be a piece of track in the form of a solid bridge which is picked up bodily and replaced by the lock tender, or hinged to swing up and allow the door to open and shut.

129. Lock Tender.—A specially reliable man of some force of character and strength of arm who can stop men from going in and out on the muck tap or interfering with the orderly work of the locks, must be on duty at all times and held to account for the operation and maintenance of the locks. It must be remembered that the men in the air chamber are helpless if all the locks are open to the normal air side. The lock tender should be provided with telephone connections both with the heading and the surface, and gauges should be provided so that he can tell at all times what the pressure is in the air chamber as well as in all the locks.

FIG. 101.—An air-lock bulkhead wall. The normal or low pressure side. Emergency lock at top, man lock on right side, material lock at bottom. (Courtesy of *New York Transit Commission.*) (*Photo by P. P. Pullis.*)

130. Location of Locks in Parallel Tunnels.—It is worth noting that if two tunnels are driven parallel to each other and close together it is advisable where the ground is open, to place the locks on the same transverse line, because otherwise the air may leak through the lining and the ground from the tunnel with the higher pressure into that with the lower pressure.

SAFETY APPLIANCES FOR USE IN COMPRESSED AIR

131. Necessity for Safety Equipment.—In compressed air tunnel work under water there come moments when the men working in the compressed air chamber are in serious danger of their lives, and certain appliances are provided to give the men a chance to escape when the time comes that they must abandon the tunnel.

132. Safety Appliances.—The safety appliances are

(*a*) The emergency runway.
(*b*) The emergency air lock.
(*c*) The safety screen.
(*d*) The lock extension.

133. The Emergency Runway.—In most modern specifications for compressed air tunnels there is a clause reading about as follows. (*New York Transit Commission.*)

"The contract shall provide a substantial runway, at least 3 feet wide, leading from the shield platform to a platform at emergency lock. Runways shall be provided with a handrail and with steps or ladders at frequent intervals for access from the track level. Runways shall be kept clean at all times.

This explains what is meant, namely an overhead footway on which the men can reach the bulkhead wall and the emergency lock with safety, even though the lower part of the tunnel is flooded. The gangway is made of three or four planks laid side by side lengthwise of the tunnel and supported either on beams placed athwart the tunnel at intervals of 12 to 15 ft. or by hangers attached to the lining. At all times, and especially when passing through treacherous ground, great care must be taken to keep the runways rigorously clear of obstructions. A wire rope hand rail should be provided at least on one side and preferably on both sides. During a blow the tunnel "fogs up" with the drop of air pressure and the men must not be exposed to the risk of

falling off the runway during such a crisis. The runway can be used only in tunnels where the headroom is sufficient, which means when the internal diameter is about 15 ft. or more.

134. The Emergency Lock.—The emergency lock has been dealt with in previous paragraphs. Even in tunnels of insufficient size to have a runway the emergency lock should be provided and placed as high as possible at all times with stairs for access to the lock. It should be open toward the air so as to be immediately accessible in time of need, and for the same reason it should not at any time be used for any other purpose than that for which it is intended.

135. The Safety Screen.—The safety screen is an air tight diaphragm placed across the upper part of the tunnel between the shield and the emergency lock. The function of the safety screen is to prevent flooding of the upper part of the tunnel between the screen and the lock by forming in effect a diving bell in which the air is retained, preventing the water from rising above a certain level. The lower edge of the screen should be placed at a horizontal plane below the entrance to the emergency lock.

136. Specifications for Safety Screen.—The safety screen is such a vital protection for the men that usually it is called for in modern specifications about as follows (*Nhw York Transit Commission*):

"In each heading chamber, when the same extends beyond the river bulkhead line the contractor shall provide a safety screen extending from the spring line of the tunnel to the top. It shall be made of at least 5/16-in. steel plate, have air tight joints, shall be substantially braced and shall be of a pattern approved by the engineer. It shall be moved forward as the shield progresses and it shall never be more than 115 ft. in the rear of the shield."

137. Origin of Safety Screen.—It is worth recalling that the safety screen was originally suggested in the Scientific American of Aug. 21, 1880, by Van der Veyde. The idea was prompted by the disaster of July 21, 1880 on the Hudson tunnel, where 20 men lost their lives in a flood caused by a blow. The inrush was so sudden that the exit was flooded before the men could reach it.

138. Construction of Safety Screen.—The safety screen may be made of wood or steel. In the Greenwich tunnel (E-11), 11 ft. 9 in. inside diameter, the screens were made of grooved and tongued planking, set vertical, stiffened with horizontal walings

and stayed with raking struts. The safety screen in this tunnel offers a proof that it can be used in a tunnel of rather small size. In the Concorde Metropolitain (F-12) tunnel the safety screen consisted of two layers of 3-in. planks, one horizontal and the other vertical, with two layers of tarred felt between them. On the Pennsylvania Railroad tunnels under the East River the safety screen was made of steel.

139. The Lock Extension.—The lock extension does not form part of the appliances for escape in case of a flooded tunnel, but is an apparatus for releasing a lock when leakage of air around the door prevents decompression from taking place. If there

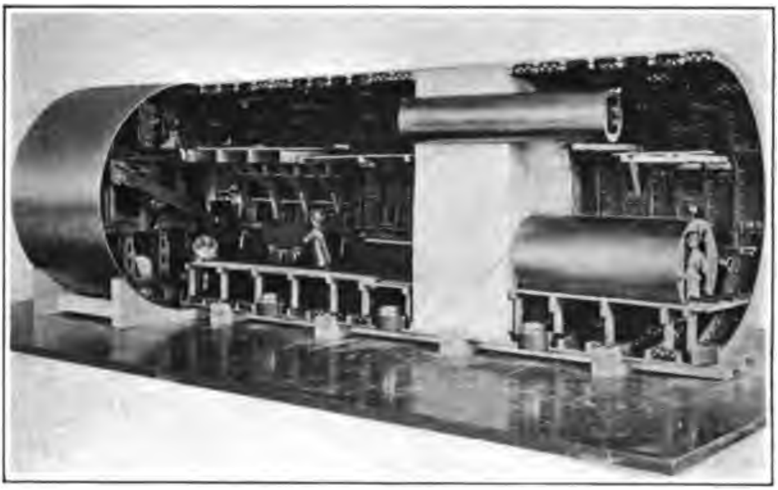


FIG. 102.—Sectional view of model of compressed air tunnel (A-18) looking toward rear of shield. (Courtesy of *Pennsylvania Railroad*.)

is more than one lock the condition is not serious, but with only one lock no other means exist for passing through. On page 225, vol. 181, *Proc. Inst. C. E.*, it is described how Benjamin Baker and young Haskin were trapped in the lock of the Hudson tunnel. The inner door fitted badly and only after many hours work did they succeed in smearing the door with mud to such a degree that the air pressure could be reduced, so that they could escape. The lock extension is a means of escape in case of such an accident, and it is described on page 241 of the same paper. It consisted of a short cylinder about 4 ft. long and 4 ft. in diameter, open at one end and having there a flange that could be bolted to the end of

any of the locks in the Hudson tunnels. At the other end was an ordinary lock door opening into the cylinder. If the regular lock door refused to work, this extension would be bolted on the outside, the regular lock would be abandoned and the locking out would take place in the lock formed by the extension, using the outer lock door as the inner door of the lock. It was used at least once with success on these tunnels, but we know of no other tunnel where it has been used.

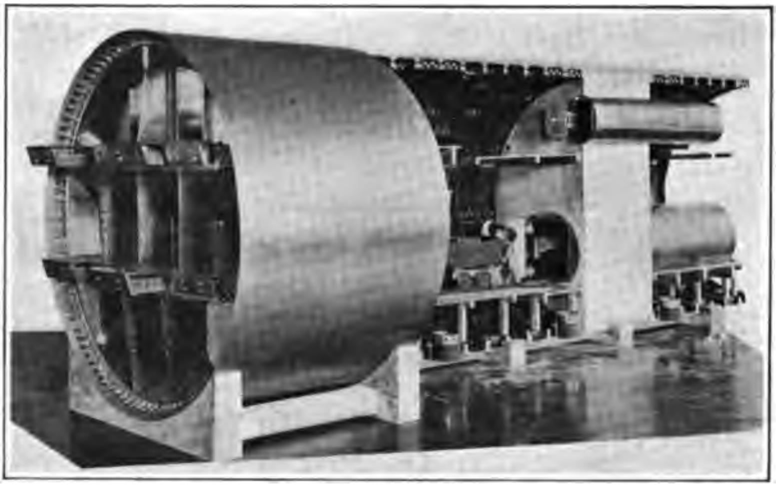


Fig. 103.—Sectional view of model of compressed air tunnel (A-18) looking toward face of shield. (Courtesy of *Pennsylvania Railroad.*)

140. Interior View of Tunnel.—Figures 102 and 103 are given to show the general interior arrangement of a shield driven tunnel under compressed air. These are photographs of a sectional model made of the Pennsylvania Railroad Hudson River Tunnels (A-18). They give a clearer idea of what a tunnel looks like than any photograph of an actual tunnel. Practically the only thing not shown is the safety screen.

CHAPTER XI

SURFACE PLANT

1. Items of Plant.—The surface plant for a shield driven tunnel consists of:

(*A*) The items which supply compressed air to the tunnel when driven under air pressure and the power for driving the various implements used in the construction of the tunnel. This will be called the power house plant.

(*B*) The items which deal with the receipt and distribution of materials for the tunnel, the disposal of spoil from the tunnel, the maintenance of the tunnel plant and similar surface activities. This will be called the yard plant.

(*C*) The offices and men's quarters.

(*A*) THE POWER HOUSE PLANT

2. Items of Power House Plant.—The power house plant may be classified as follows:

(*a*) The low pressure air compressing plant, used to supply compressed air to the air chamber. This plant is used only when the tunnel is driven under air pressure.

(*b*) The high pressure air compressing plant, used to supply compressed air for rock drills, grouting machines and other tools and machines or appliances worked by compressed air.

(*c*) The hydraulic plant, used to generate the power by which the shield is driven and operated.

(*d*) The electric power plant, used to supply current for lights and electric power appliances used in the tunnel and on the surface.

(*e*) The machine shop plant.

(*f*) The boiler plant or the other sources of power by which the items of power house plant are driven.

(*a*) THE LOW PRESSURE AIR COMPRESSING PLANT

3. Purpose of Plant.—The purpose of the low pressure air compressing plant is to furnish the compressed air used in the

portion of the tunnel which is kept under air pressure during the construction.

4. Pressure Required.—The pressure at which the air must be delivered to, and maintained in, the tunnel is a function of the hydrostatic head on the tunnel, the character of the ground and the size of the tunnel. If the ground is close and possesses some cohesion the pressure used to keep the tunnel dry is approximately equal to the head of water above the invert of the tunnel. If the ground is open such a pressure generally cannot be used on account of the danger of disrupting the ground and causing a blow. Usually in that case the pressure used will balance the head of water either at the top or at the middle level of the tunnel. In such case the lower part of the tunnel cannot be kept dry by the air pressure. In soft mud with little or no cohesion, through which the shield may be driven blind, the pressure of the air may be less than the hydrostatic head as long as no work is carried out ahead of the shield. If it is necessary to work in front of the shield diaphragm, however, the required pressure will approximate the combined pressure of water and mud above.

5. Volume Required.—If no leakage of air occurred either at the face or at the bulkhead, then after the tunnel once had been filled with air at the required pressure, the volume of air required to be furnished to the tunnel for maintaining this pressure would be independent of the diameter of the tunnel and its length and would depend only on the additional volume excavated from time to time. Under such ideal conditions, which in any case are only approximated in actual construction, it is necessary to ventilate the air chamber to make the air fit to breathe by the men working in the tunnel. This means that a certain volume of fresh air, depending on the number of men in the tunnel, must be introduced constantly into the tunnel and a corresponding volume removed to maintain the pressure. In most cases, however, the volume required will be determined by the leakage.

6. Sources of Leakage.—The constant use of the air locks is one source of leakage; this usually is unimportant except when the air chamber is short. Another source is the joints between the segments of the tunnel lining, the importance of this source being greatest when the ground is open and the construction carelessly done. The two most important sources of leakage, however, are the clearance between the outside of the

lining and the tail of the shield, and the face of the ground which is uncovered in order to proceed with the excavation.

7. Measure of Volume.—The volume of compressed air delivered is generally measured at normal air pressure, for example, if 2,000 cu. ft. of air is delivered in the tunnel at a gauge pressure of 29.4 lb. per square inch this is measured as 6,000 cu. ft. of air at normal pressure.

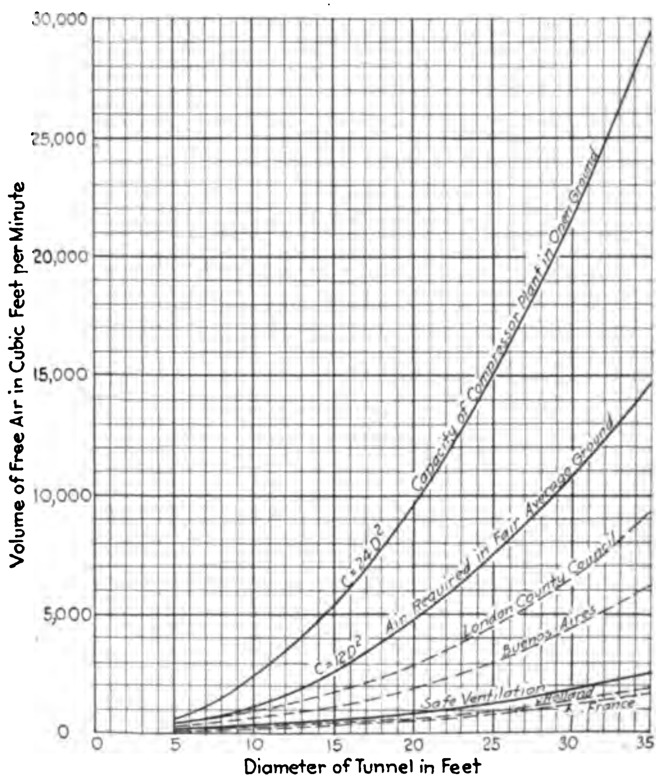


FIG. 104.—Relationship between diameter of tunnel and capacity of low pressure air compressor plant.

8. Volume Required for Ventilation.—On the Hudson River tunnels of the Pennslyvania Railroad (A-18) records were constantly kept during the construction of the quantity of air delivered per man. While the tunnels passed through the silt the leakage was small and the air was introduced for ventilation. On certain occasions the supply was as low as 20 cu. ft. per man

per minute and after a series of experiments it was found that no increase in volume of over 35 cu. ft. of free air per man per minute (at the usual pressure of 26 lb. on the gauge) had any additional beneficial effect on the health of the men. The curve corresponding to this volume for an average number of men working in the tunnel is plotted on Fig. 104, on which also some other curves are plotted; these will be described later. The volumes as shown by the curve are suggested as safe, liberal allowances under gauge pressures up to 25 or 30 lb. per square inch. If the pressure rises beyond 30 lb. per square inch it might be advisable to increase the supply, possibly to 65 cu. ft. per man per minute.

9. Volume Required by Authorities.—In some countries the minimum volume of air to be delivered is determined by laws or regulations of public authorities and in some cases it is included in the specifications for the construction contract. Table XIX shows the volume of free air in cubic feet per man required in certain countries.

TABLE XIX.—MINIMUM ALLOWANCE OF AIR REQUIRED BY LAWS AND REGULATIONS

Country	Authority	Volume of free air per man in cubic feet	
		Per hour	Per minute
England	London County Council, 1904	8,000	133.0
Holland	Royal Ordinance, June, 1905	1,588	26.5
France	Law of December, 1908	1,423	23.7
Argentina	Intake Tunnel, Buenos Aires	5,295	88.3

In Chap. XV there is a discussion giving the number of men that may be expected to work at one time or in one shift in compressed air in tunnels of different diameters. Using these figures, the following table (Table XX) indicates the total volume that would be required as a minimum allowance.

These values are also plotted in Fig. 104. The official requirements of the London County Council of 8,000 cu. ft. per man per hour have been relaxed in actual practice. Volumes of 4,000 to 5,000 cu. ft. per man per hour or 67 to 84 cu. ft. per man per minute have been permitted. In other words, the actual practice of the London County Council approximates the volumes called for by the Buenos Aires authorities.

TABLE XX.—COMPUTED MINIMUM ALLOWANCE OF FREE AIR IN TUNNELS

External diameter of tunnel, feet	Average number of men in compressed air	Volume of free air required per minute by public authorities, as under, in cubic feet			
		London	Holland	France	Buenos Aires
5	7	930	190	170	620
10	11	1,460	290	260	970
15	19	2,530	500	450	1,680
20	30	4,000	800	710	2,650
25	44	5,860	1,170	1,040	3,880
30	61	8,130	1,620	1,450	5,390
35	82	10,930	2,900	1,940	7,240

10. Carbon Dioxide.—In some cases the contract specifications have determined the maximum percentage of carbon dioxide (CO_2) permitted in the working air chamber. The French compressed air regulations specify that the volume of carbon dioxide gas present in the working chamber shall not exceed one part of CO_2 gas in 1,000 parts of the tunnel air. The same specifications are found in the contract for the Pennsylvania Railroad tunnels at New York (1904–1906) as well as in those for the tunnels under the East River, built in 1914–1916 by the Public Service Commission for the First District in connection with the rapid transit lines in New York City. With a volume of 35 cu. ft. per man per minute as suggested, the volume of carbon dioxide will be found usually to be below that specified. In Chap. XVII further reference is made to this matter of CO_2. The modern opinion is that the CO_2 content has no direct effect on compressed air sickness.

11. Volume Required by Leakage.—When the ground is open the volume needed to maintain the pressure will exceed usually that determined by the minimum requirements stated above. What the volume will be is a matter of judgment and experience rather than of precise computation. The leakage may be assumed to be proportional to the square of the diameter in ground of the same character. The following table (Table XXI) gives particulars about the low pressure air compressor plants in some of the compressed air tunnels about which details have been published.

TABLE XXI.—CAPACITY OF COMPRESSOR PLANTS USED ON CONSTRUCTION OF TUNNELS

Ref. No.	Tunnel	Outside diameter D, feet	Number of tunnels, N	Capacity of plant, cubic feet per minute, C	$\frac{C}{ND^2}$	Note
(E-7)	Blackwall	27.00	1	10,000	13.8	*A*
(E-15)	Baker St. & Waterloo	12.81	1	3,200	19.4	*B*
(E-17)	Rotherhithe	30.00	1	16,667	18.5	*C*
(A-17)	Hudson & Manhattan	{19.50 16.58}	2	8,954	13.7	*D*
(A-17)	Hudson & Manhattan	16.58	2	5,040	9.2	*E*
(A-17)	Hudson & Manhattan	16.58	2	5,550	10.0	*F*
(A-17)	Hudson & Manhattan	16.58	2	10,840	19.7	*G*
(A-18)	P. R. R. Hudson River	23.00	2	13,167	12.4	*H*
(A-18)	P. R. R. Hudson River	23.00	1	13,167	24.8	*I*
(A-19)	P. R. R. East River	23.00	4	35,000	16.6	*J*
(A-19)	P. R. R. East River	23.00	4	45,000	21.3	*K*
(A-19)	P. R. R. East River	23.00	1	19,000	35.9	*L*
(F-12)	Concorde Metropolitain	25.54	1	9,500	14.6	*M*
(E-11)	Greenwich	12.75	1	1,640	10.0	*N*

The following notes refer to the letters in the last column of the table.

(*A*) The Blackwall tunnel was driven through open gravel. While passing through the gravel the whole capacity of the plant was used.

(*B*) The Baker Street and Waterloo Railway tunnels, of which there were two under the Thames were not driven at the same time. The second was not started until the first was completed. Copperthwaite states that on one occasion a good deal of water was let into the tunnel on account of deficiency of air pressure.

(*C*) The Rotherhithe tunnel was driven mostly through close ground. No important leakage occurred and the plant was usually driven only at half its capacity.

(*D*) Hudson and Manhattan tunnels. Mostly close ground.

(*E*) Hudson and Manhattan tunnels. Silt.

(*F*) Hudson and Manhattan tunnels. Silt.

(*G*) Hudson and Manhattan tunnels. Sand and gravel, part rock and part silt.

(*H*) Pennsylvania Railroad, Hudson River. Rock, part rock and part sand, dense silt, river bulkhead and silt. Plant worked to capacity in open ground; in silt ventilation determined the quantity of air.

(*I*) Pennsylvania Railroad tunnels, Hudson River. Full face open sand and gravel. Only one face could be worked at a time owing to the escape of air. It is stated (*Eng. News*, Feb. 28, 1907): "The air compressors were here taxed to their full capacity for over two months without once failing."

(*J*) Pennsylvania Railroad tunnels, East River. Fine sand, sand and boulders, open beach sand, rock, sand and clay.

(*K*) Pennsylvania Railroad tunnels, East River. Same as above.

(*L*) Pennsylvania Railroad tunnels, East River. This quantity of air was supplied during a blow.

(*M*) Concorde Metropolitain. Limestone, marl, coarse black sand.

(*N*) Greenwich, River Thames. Open gravel, close sand, sandy clay and clay.

12. Leakage and Blows.—A distinction should be made between leakage and blows. The plant should be sufficient to take care of the maximum leakage, but the volume of air that may escape by a serious blow is purely problematic and depends on the size of the opening made. No plant capacity can be provided to take care of that.

13. Capacity of Plant Determined by Maximum Volume.—A tunnel is rarely driven through the same kind of material throughout, and the volume of air required may vary greatly from time to time during the construction, but the capacity of the plant must be sufficient to supply the needed air, even when the leakage is greatest. The capacity of the plant should be determined, therefore, by the maximum volume estimated to be needed and not by the average volume.

14. Capacity of Plant.—Judging from previous experience the capacity needed for one tunnel in fairly average open ground may be expressed by

$$C = 12D^2 \tag{44}$$

where C is the capacity in cubic feet of free air per minute, and D the external diameter of the tunnel in feet. In open sand and

gravel and similar ground the capacity required may be expressed by

$$C = 24D^2 \qquad (45)$$

These formulas are plotted and are shown in Fig. 104.

15. More Than One Heading.—In tunnel work where more than one heading is driven at one time and where the distances over which the maximum capacity will be required are limited, work may be discontinued in some of the headings, while going through the stretch where a large volume of air is required. The compressors of the complete plant may be concentrated on the headings at work, so that the total compressor plant in this case will be less than if work was carried on in all the headings at one time.

16. Spare Compressor Plant.—It is necessary to allow a certain margin of compressor plant above that stated in par. **14** to allow for break-downs and repairs. On the Rotherhithe tunnel, (E-17), the specifications called for a complete duplication of all plant. Air compressors of modern make are of such a high degree of reliability that this seems unduly severe. An excess capacity of from 25 to 50 per cent would seem adequate insurance.

17. Arrangement of Plant.—Compressors of reliable make and well tested by actual use should be chosen. They should be installed with care, inspected and maintained in the best of condition at all times and a sufficient supply of spares of all parts liable to break or wear out should be kept on hand. The power house should be laid out in such a way that additional units of air compressors may be put in without disturbance to the rest of the plant in case it is found that the capacity of the plant first laid down is not enough.

18. Several Units Preferable.—It is better to divide the capacity among several units than to install one machine capable of delivering the whole supply. Suppose, for example, a tunnel of 25 ft. diameter is to be driven in what is expected to be an average bed of open ground. According to equation (44) the net capacity of the plant should be 7,500 cu. ft. per minute. Allow an excess capacity of 50 per cent, making the total capacity 11,250 cu. ft. per minute. This plant could be divided into 3 units of 3,750 cu. ft. each. Under normal conditions two of these units can supply all the air required, thus enabling the third to remain as a stand-by in case repairs are needed, and if the leakage should be greater than anticipated, all three units may be

used. If the leakage of air should prove greater even than what can be taken care of by the three units, another unit may be installed, bringing the total capacity up to that estimated for very open ground.

19. Standardization of Plant.—It is advisable to standardize the compressor plant as well as other plants as much as possible to avoid confusion and to reduce the necessary number of spare parts.

(*b*) High Pressure Air Compressing Plant

20. Purpose.—The high pressure air compressing plant is used to supply the power to the rock drills, grouting machines, pumps, hoisting engines and other tools and implements driven by compressed air.

21. Capacity Required.—The required capacity of the compressors may be computed by adding the consumption of all the tools and implements that it is estimated will be in use at the same time. As a guide in making this estimate it may be stated that from previous experience it appears that for rock drills 10 cu. ft. of free air per minute are needed per square foot of face covered by rock, and that for grouting 1 cu. ft. of free air per square foot of face per minute is needed.

22. Use of Low Pressure Air Compressors.—When the low pressure air plant is not running to its full capacity, this may be used to assist the high pressure air plant. On the Hudson River tunnels of the Pennsylvania Railroad during such time as the headings were mostly in rock and much air was needed for the drills, the full capacity of the low pressure compressors was not needed. Compressed air was then furnished from the low pressure plant into the air cylinders of the high pressure compressors. In this way the capacity was increased 4,400 cu. ft. of free air per minute. On the East River tunnels of the Pennsylvania Railroad, in addition to the regular high pressure air plant, a combination machine was installed which could be used either as a high pressure compressor or as a low pressure machine. As a low pressure compressor it had a capacity of 5,000 cu. ft. per minute; as a high pressure compressor it could compress 1,600 cu. ft. of free air up to 90 lb. gauge pressure with atmospheric intake or 6,900 cu. ft. to 140 lb. with an intake pressure of 50 lb.

23. Gauge Pressure.—The gauge pressure at the compressor will depend on whether the tunnel is driven under compressed air or in normal air and on the friction loss in the pipe. When driven under compressed air the gauge pressure should be from 140 to 150 lb. per square inch, if a pipe of a reasonable size is used for delivery. The air tools work best at a pressure of from 90 to 100 lb. above that of the air in which they are being used, that is to say, if the air pressure in the tunnel is 30 lb. per square inch the delivery pressure should be from 120 to 130 lb. per square inch.

24. Efficiency Pays.—In all tunnel power plant lay-out it pays to remember that the real economy lies in the output of as many units of tunnel work per unit of time as possible and not in comparatively insignificant economies of power house equipment and installation. Time in these matters is "of the essence of the contract" to the contractor equally with the owner. There is nothing more disheartening, not only to the contractor himself, but to every worth-while man in his tunnel gang to find the drills feebly pecking at the rock, because the air pressure has not got the punch. Get good reliable machines of ample capacity and giving ample pressure, put in pipe lines that are thoroughly well installed and maintained and of ample size, and then the men on the job have a chance to show what they can do.

(*c*) Hydraulic Pressure Plant

25. Purpose.—The hydraulic pressure plant is used to work the shield, by supplying the power to the propelling jacks, the face jacks and the segment erector.

26. Pressure Used.—For modern shields the hydraulic plant and equipment is generally made capable of developing and working under a pressure of 5,000 lb. per square inch; 6,000 lb. pressure has been used.

27. Capacity of Plant.—It may be assumed that the shield jacks are used when the other hydraulic equipment of the shield is not in operation. The capacity of the hydraulic compressors will then be determined by either that required for the shield jacks or that for the other hydraulic equipment.

28. Capacity Required for Shield Jacks.—Consider first the shield jacks: the volume of water to be delivered will be a function of the cross-sectional area and number of the shield

jacks and of the distance the plunger of a shield jack travels per minute in relation to its cylinder. In modern shields the total jack pressure provided may be taken as lying between 70 and 140 lb. per square inch of the cross section of the tunnel. If D is the external diameter of the tunnel in feet and A is the total cross-sectional area of the shield jacks in square inches, then A will lie between the limits of $1.63D^2$ and $3.26D^2$. Let it now be assumed that it is desired to provide for an advance of the shield of 3 in. per minute for the lower value of A and $1\frac{1}{2}$ in. for the higher value, then the net displacement Q in U. S. gallons per minute in the first case is $Q = 1.63D^2 \times 3/231 = 0.0212D^2$, and in the second case $Q = 3.26D^2 \times 1.5/231 = 0.0212D^2$. The required displacement is the same, therefore, in both cases. To this displacement should be added about 10 per cent to allow for leakage. The net capacity of the hydraulic pressure plant in gallons per minute C may then be expressed by

$$C = 0.233D^2 \tag{46}$$

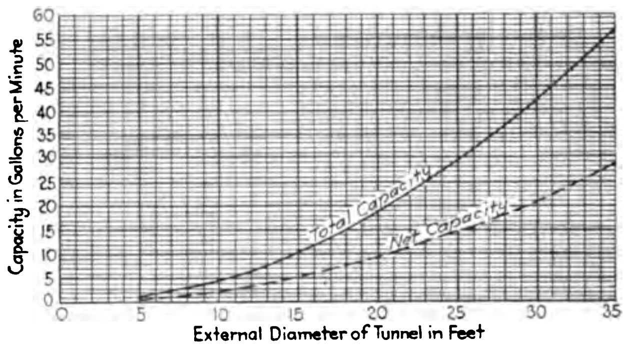


FIG. 105.—Relationship between diameter of tunnel and capacity of hydraulic power plant.

29. Capacity Required for Other Equipment.—A similar investigation should be made of the other hydraulic equipment of the shield and the required capacity determined. Usually it will be found that the requirements for the shield jacks will be the greater.

30. Spare Plant.—Owing to the high pressure under which the hydraulic plant is operated it is likely to get out of order and it is advisable to install a plant of double the capacity computed.

31. Diagram of Capacity.—Figure 105 shows the curve of the equation in par. **28,** giving the net required capacity and also a

curve giving the double of this capacity, which is the capacity of the plant that should be installed.

(d) Electric Light and Power Plant

32. Purpose.—The purpose of the electric light and power plant is to furnish the current required for lighting the tunnel and the working site and for supplying the power to the various tools and plant operated by electricity.

33. Capacity of Plant.—The capacity of the plant must be calculated from the aggregate current consumption required to operate the various items of plant and tools and to furnish the necessary lighting. The matter of the spacing of the lights required in the tunnel itself is dealt with in Chap. X, par. **39**. The total number will depend on the length of tunnel to be built. The other lights will be those for the offices and power house, machine shops, men's quarters and other buildings and for the yard itself; since tunnel work is carried on usually by night as well as by day a full allowance of lights should be provided. For the yard there is nothing so good as arc lights which can be used to flood the whole area with light almost equal to that of day.

34. Current from Outside Source.—In cases where the tunnel work is being done where public service electric current of a reliable nature is to be had, it may be an open question whether an electric generating plant at the works is necessary or justified. Generally it may be said that the uninterrupted supply of current to the works is so important that a generating set should be put in even if only to act as a stand by in case of interruption to the public supply.

(e) THE MACHINE SHOP

35. Use of Machine Shop.—It will be necessary to make constant repairs and alterations to the plant, both portable and fixed, both surface and underground. It is necessary, therefore, to provide a well equipped workshop so that these repairs and alterations may be carried out on the spot, thus avoiding the expense and delay of having them done outside. No attempt will be made to specify or describe in detail the equipment for such a workshop but the following list will give some idea of the tools needed.

Drill bit sharpening machines.
Blacksmith tools.
Drill presses.
Lathes.
Pipe cutting and threading machine.
Bolt cutting and threading machines.
Punching and shearing machines.
Steam hammers.
Saw benches.
Band saws.
Rotary saws.
Planers.
Planers and molders.

(*f*) The Boiler Plant or Other Source of Power

36. Selection of Source of Power.—In places where there is an abundant supply of reliable electric power, the power house plant may be driven by electricity.

37. Difficulties with Air Compressors.—There is a difficulty, however, in connection with the use of electric power to drive air compressors. The speed of the motor cannot be changed and consequently there is no way of regulating the volume of air discharged. When electric power has been used certain expedients have been adopted. In some cases the plant may contain electrically operated compressors with other units driven by steam. The electric compressors may then discharge their output into one or more tunnels requiring more than their total volume and the deficiency is taken care of by the steam units.

38. Flexibility Necessary.—In a compressed air tunnel the volume of air required at any given time depends on the character of the ground being penetrated at that moment. The ground is liable to change rather suddenly so that there should be a flexible delivery of air. This is achieved more readily with steam than with electric power.

39. Steam Power Preferable.—Steam power also has drawbacks. It takes up more room; it involves the handling and storage of coal; some of the energy produced is wasted, because it cannot be proportioned exactly to the work required. Nevertheless, it is believed that, with things as they are now, steam operation is the proper choice for heavy work.

40. Boiler Capacity.—The boiler capacity necessary for any given case has to be computed from the items of plant which the steam will operate. The following table, Table XXII, shows the horse power actually used at several compressed air tunnels.

TABLE XXII.—HORSE POWER OF COMPRESSED AIR TUNNEL PLANTS

Ref. No.	Tunnel	Outside diameter, feet	Number of tunnels	Total cross-section A, sq. ft.	Boiler horse power, P	$\frac{P}{A}$
(A-19)	P. R. R. East River, N. Y.	23.00	4	1,662	3,000	1.81
(A-19)	P. R. R. East River, Long Island	23.00	4	1,662	4,200	2.54
(A-18)	P. R. R. Hudson River, N. Y.	23.00	2	831	1,800	2.17
(A-18)	P. R. R. Hudson River, N. J.	23.00	2	831	1,800	2.17
(F-12)	Concorde Metropolitain	25.54	1	512	1,100	2.15

(*B*) THE YARD PLANT

41. The Working Site.—The first item in the yard plant is the working site. This is located at and around the shaft from which access is had to the tunnels under construction. It is occupied by the storage yard, storage buildings, power house, offices and men's quarters and other facilities.

42. Size of Yard.—The working site should be large enough to permit the work to be done efficiently. The proper size will be affected by the size of the tunnel, the number of headings and the character of the work. It is difficult to give any definite figures as to the actual area required, but from previous experience it may be said that an area of from 100 to 150 times the total cross-section of the tunnels worked at one time will be about right. If only one tunnel is driven the necessary area per unit of tunnel cross-section will be larger than if two or more are constructed at once.

43. Cages.—To handle the material through the shaft, elevators or cages should be provided. These must be equipped with safety devices so that they cannot be "overwound" into the head gear nor dropped to the bottom of the shaft. Catches or chains

must be provided in the cages so that cars being hoisted cannot drop out. Safety gates should be provided at top and bottom so that men cannot walk into the cage-way. At the top of the shaft around the cage automatic covers lifted and lowered by the cage itself should be provided to prevent things dropping down the shaft.

44. Derricks.—Derricks are required to load and unload materials. Locomotive cranes are useful in places where materials have to be transferred.

45. Railroad Tracks.—If the yard is near a railroad a siding should be provided for transfer of materials.

46. Storage Space.—Storage space must be provided for the materials of construction, such as sand, stone, cement, tunnel lining, etc. The sand and stone should be stored in elevated bins. The cement must be stored in waterproof sheds. Tunnel segments may be piled up on the ground. Segments of different patterns should be stored in separate piles. Further storage space must be provided for coal, dynamite, lumber, tools and other things.

47. Stone Crusher.—Where the rock excavated is suitable for concrete aggregate a stone crusher may be an economical investment.

48. Waterfront Equipment.—Where the yard adjoins navigable water the materials to be received and disposed of may be handled by water traffic, which usually is more economical than other methods.

49. Pug Mill.—If tempered clay cannot be obtained for "pugging up" it may be necessary to have pug mills to work the raw clay.

50. Traction.—To move cars around the yard men, mules or electric traction may be used. Men should be used only where no other means are possible.

(*C*) OFFICES AND MEN'S QUARTERS

51. The Engineer's Office.—Where the work is going on for 24 hours a day a large proportion of the engineering staff will be working in shifts. Consequently, there is on any piece of work of large size a number of engineers and inspectors that must have allotted to them room for their clerical, cement testing, photographic and other routine work and there must be provided

also locker rooms in which each man will keep his clothes. As a general rule the men on duty will have to eat a meal in the offices and a room may be set apart for this purpose. Adequate toilet and washing accommodations with hot and cold water must be provided, including shower baths. The engineers should have their own hospital lock and their own means for making the hot drink which is a necessity in compressed air work. The engineer's quarters should be looked after by a special janitor day and night. The engineer in charge should see that scrupulous neatness and cleanness is kept throughout. In the locker rooms a certain quantity of tunnel dirt will be brought in as the men come up from below with mud all over them, but it should not be permitted to remain there. It is a good idea to have a tub of water in which the men can wash off their rubber boots before coming into the offices. Good work cannot be done in a pig sty. Many a young engineer likes to glory in the dirt and roughness of his work. This is a great mistake. Down below he must be prepared to get as dirty as may be. When he reaches the surface he should shed this dirt and become once more a clean and civilized being. The engineer in charge should have his own private office and his own wash room. A certain reserve is essential and his authority must not be risked any more than must that of a captain of a ship.

52. Offices for Construction Staff.—By the construction staff is meant the men who perform the executive and administrative functions of the actual construction. They will include the general superintendent and his chief assistants such as the assistant general superintendent, the general tunnel superintendent and the chief medical officer. To be housed in the offices will be resident doctors, doctor's assistants, master mechanic, chief electrician, concrete foreman, chief carpenter, timekeepers, telephone operators, office boys, messengers and janitors. The same requirements apply to these offices as to those of the engineer. Dark, ill ventilated, dirty and unheated shacks are not proper places in which the responsible work of building a tunnel should be done. The offices should be laid out with as much care as though they were those for a commercial enterprise. Each man should have his own locker, each responsible head of a department his own room. There are occasions when the head of the department will have to sleep on the job and accommodations should be made for this. The doctor's office should be

ample in size and fully equipped with everything the doctor may call for. The men should not be led to think that their hurts are not being attended to with the greatest possible skill and care.

53. The Men's Quarters.—The men's quarters should receive the same care and attention as those of the engineers and of the administrative staff. In a large tunnel work with several shields being driven at once, and especially in high air pressure, where the shifts are short, the number of men employed runs up to a large total. In planning the men's quarters liberal estimates should be made of the probable total number of men. An individual locker should be provided for each man. Drying rooms should be set aside to dry the wet clothes as the men come up from below and a man should never have to put on clothes still wet from the previous shift. The washing accommodations should be ample. Provide enough wash basins so that all the men in one gang can wash at one time and enough shower baths to avoid keeping men waiting. Hot and cold water, soap and towels should be provided without stint. Hot sweet coffee, or preferably hot beef extract, must be given the men freely. Janitors should be held responsible for a clean and tidy condition of the wash rooms and the toilets. A good light room for eating and for the men to rest in, if the shifts are broken, should be provided. The tunnel men proper should have distinct quarters from the power house men and the surface force. These are the men on the firing line. When the blow comes these are they who stand breast to breast with the trembling ground and who have thrust their very bodies into the forming crater to save the tunnel. Their work is hard, it is done in the depths far from the cheerful sunlight. They deserve decent comfort and attention.

CHAPTER XII

CONSTRUCTION

INTRODUCTION

1. Fundamental Principles.—The process of driving a shield must be done in such a way that the greatest possible speed of advance is attained with the least possible danger to the tunnel or to nearby structures. The first object is reached by a suitable design, an efficient working force and an adequate and suitable plant. To obtain the second the face of the excavation must be under complete control at all times, that is to say, there must be no movement of the ground through which the tunnel is driven except of that portion immediately in front of the shield which has to be removed to allow the shield to move forward. Difficulties will be met in the course of driving. It is essential that the engineer should be able to forestall these difficulties, recognize them when he sees them and know how to overcome them.

2. Purpose of Using Shield.—The principal function of the shield is to support the ground around the tunnel excavation until the lining has been placed. The more support is needed the more applicable is the shield method. In firm rock and in certain kinds of stiff ground, the excavation will stand unsupported for quite some time. In such ground a shield is not needed and is, in fact, an impediment. If the ground is of varying character along the course of the tunnel the shield may be essential for part of the way and it may be necessary to carry the shield through the portions that do not need its assistance.

3. Work Involved in Construction.—The work of building a shield driven tunnel consists essentially of:

(*1*) Excavating the ground.
(*2*) Erecting the lining.
(*3*) Completing the interior finish.

In shield driven tunnels the first two processes are carried out at one time and the methods used are independent of the purpose for which the tunnel is to be used. The last process depends

on the final use of the tunnel and does not come within the scope of this book.

4. Synopsis of Chapter.—This chapter and that following will treat of the work of construction under the following heads

(*A*) Excavation.
(*B*) Blows and blankets.
(*C*) Driving shield.
(*D*) Erecting lining.
(*E*) Grouting.
(*F*) Calking and grummeting cast iron lining.
(*G*) Engineer's supervision.

(*A*) EXCAVATION

5. Excavation Methods Depend on Ground.—It is the ground itself which dictates the method of excavation to be used in any given case. The ground may be dry or wet, it may be rock, clay, gravel or sand, part rock and part soft ground, mud or mixtures of these. An outline of the methods used for these kinds of ground will be attempted in this chapter.

6. Design of Shield.—The shield is the main working implement used in the construction. Its proper design for the kind of ground in which it is to be driven is essential for the successful and economical performance of the work. The matter of shield design is treated in Chap. IX.

(*A*-1) EXCAVATION IN ROCK

7. Excavation in Rock, Reason for Using Shield.—In solid rock the shield makes a poor showing. The method is unsuited to the material. In many cases, however, it is necessary to take the shield through solid rock. For example: a shield driven tunnel may have to be started in a solid rock formation and driven through this for some distance before the soft and waterbearing ground, in which the shield has its true home, is reached. Or a ledge of rock may have to be traversed in an otherwise soft ground tunnel. Or perhaps a succession of soft waterbearing seams of decomposed rock are found between stretches of sound rock. In such cases the shield may have to be driven through the sound rock in order to do its real duty which is confined to the decomposed zones.

8. Shield Exposed to Damage in Rock.—In solid rock the excavation is done ahead of the shield and the shield is advanced by its jacks through the space excavated. If there is any piece of rock projecting in the path of the shield the latter will suffer severely as a result of the collision. Probably more damage has been done to shields by their striking rock than by all other causes put together. Furthermore, the rock has to be excavated by blasting and it is impossible to prevent flying fragments of rock striking the shield. This batters and bends the structural members of the shield and may weaken it to such an extent that serious deformation may result. See Figs. 89 and 90.

9. Method of Carrying Shield through Rock.—As much as possible of the rock should be removed before the shield gets to it. Where the cover is ample the entire bore may be taken out so that the shield may pass through the opening thus made. It will be understood that the process in this case is not shield tunneling in the true sense, but only a matter of moving the shield forward through the rock portion of the tunnel until the proper shield ground has been reached. During the progress through the rock the shield may be used for the erection of the lining. If cast iron lining is used for the tunnel as a whole, the same material is often used through the rock portion, though possibly of a lighter weight. In that case the shield will be self-propelling. The lining will be built up in the usual manner within the tail of the shield and the shield will move forward under the push of the jacks against the finished portion of the lining. Where the cover becomes too little for the entire bore to be taken out in advance, as much as possible of the rock should be taken out in advance of the advent of the shield, even if this means merely a bottom heading.

10. Blasting in Front of Shield.—Where the full bore can be excavated ahead, notwithstanding care taken to remove all the rock before the shield comes along, there is always some trimming to be done in the immediate forefront of the shield. Where the cover is too small for the previous removal of the full bore, large quantities of rock must be removed immediately in front of the shield. The drilling and shooting must be done with small charges in short holes placed close together so that the rock will be broken gently and not caused to fly violently in large masses. The depths and spacing of the holes, the size of the charges and the strength of the explosive depend wholly on the character of

the rock and are best made the subject of some careful experiments early in the work. Where the cover is small and apt to vary test holes should be run upwards in the top before each shove so that no unexpected break through into soft ground may cause a disastrous run.

11. Removal of Rock through Shield.—Where large quantities of rock spoil have to be handled through a shield it is a great drawback if the muck cars cannot be run through the shield into the face or through the bottom heading. In such cases a careful study should be made in the shield design as to whether an opening can be provided in the bottom portion of the shield large enough to pass the cars. If the shield has to pass through soft and waterbearing ground after or before passing through the rock the provision of this large opening may entail a good deal of additional expense in building the shield. This expense may be small, however, in comparison with the never ending delay and annoyance caused by handling the rock through small openings intended for mud or sand. These large openings would have to be made so that they could be closed or sub-divided when the rock work was over. On the East River Tunnels of the Pennsylvania Railroad (A-19) the closed bulkhead in the bottom of the shields was found to be such a hindrance when working in the rock that the contractor cut through these bulkheads thus allowing an opening through which the cars could be run.

12. Position of Heading.—In taking a shield through rock, as in all other cases of rock tunneling, where the cross-section of the tunnel is large enough to permit the heading and bench method, the heading may be placed at the bottom, at the top, or at the middle of the cross-section.

13. Bottom Heading.—If placed at the bottom a convenient set of circumstances is created for placing the cradle (of which more later), but a disadvantage is had by reason of the fact that the great bulk of the excavation is above the heading. When firing is started the muck falls to the bottom blocking the heading and work in the heading has to cease until the mucking for the round on the face has been nearly finished (see Fig. 106).

14. Top and Bottom Heading.—In a tunnel of quite large cross-section a top heading may be driven in conjunction with a bottom heading if the cover is ample. In this way the top heading muck can be handled through the top pockets independently of the

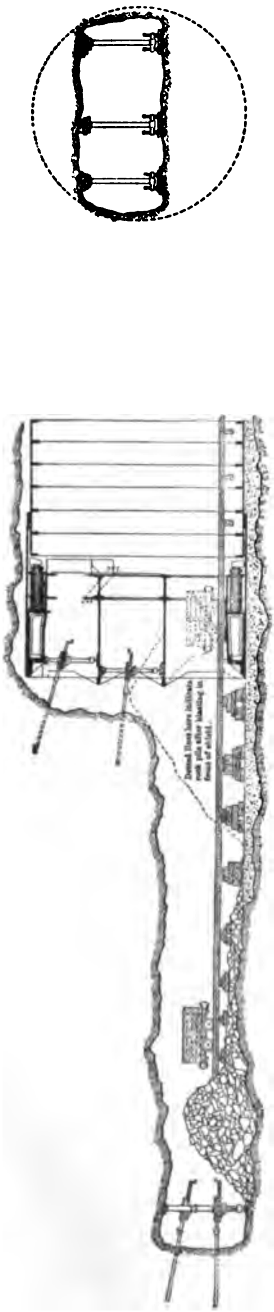


FIG. 106.—Shield in rock. Bottom heading. Pennsylvania Railroad tunnels, East River, New York (A-19). (From *Trans. Am. Soc. C. E.*, vol. 68.)

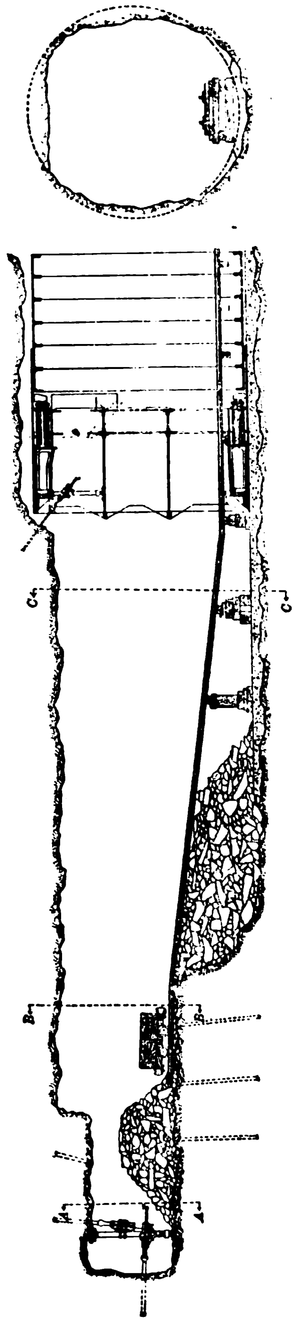


FIG. 107.—Shield in rock. Center heading. Pennsylvania Railroad tunnels, East River, New York (A-19). (From *Trans. Am. Soc. C. E.*, vol. 68.)

bottom heading and thus reduce the delay to the heading work caused by the muck from the main enlargement.

15. Center Heading.—On the East River tunnels of the Pennsylvania Railroad (A-19) it was found best to drive the heading approximately on the axis of the tunnel with the lower compartment of the shield cut away to allow the muck cars to pass through the shield. The rock below the heading was taken out as a bench in an ordinary rock tunnel. A heavy timber platform was built out from the floors of the middle level pockets to catch the muck shot from the upper pockets and thus prevent blocking the tracks below. Most of the top muck was caught on this platform. The method is shown in Fig. 107. As the timber platform did not prove entirely satisfactory, the drills in the heading were turned upward and a top bench drilled and fired. The excavation left in the top was so little that it was allowed to fall on the tracks and was quickly cleaned away. This was found to be the best method for full rock section.

16. Cradle.—A concrete invert or cradle should be built in advance of the shield. The shield slides upon this cradle and thus damage to the shield is avoided and true line and gradient are kept. The average thickness of concrete in the cradle should be not less than 4 or 6 in. Usually the inevitable overbreakage in the excavation will permit this thickness. It is usual to embed in the concrete two or three steel rails laid parallel to the tunnel and with the head of the rails projecting slightly above the concrete. The rails and the concrete must be of strength sufficient to carry the weight of the shield. The width of the cradle depends on the size of the tunnel. The outside rails should be spaced rather more than one-half the length of the radius on each side of the vertical axis, because as the lining will come to a bearing on these rails, this spacing will prevent deflection of the lining under its own weight. If a third rail is used this will be placed at the vertical axis. If the spacing of the rails is less, the rails should be set rather higher than the designed elevation to allow for flattening of the lining. This allowance might be 1 in. for a 15-ft. diameter tunnel and 2 in. for a 25-ft. tunnel. The cradle should be far enough in advance of the shield so that the concrete has time to set thoroughly before the shield comes on it. It must be built with care to the exact line and gradient as it forms the guidance to the shield and the tunnel. The cradle is not a merely temporary expedient to allow the shield to be

hustled through the rock but is a part of the permanent work and as such subject to the engineer's close study and inspection.

17. Waterbearing Rock.—The work of driving the shield in rock would be the same in essential features whether the rock were dry or carried waterbearing seams. If these were present it would be feasible to remove the water by pumping. In work of this kind, where full rock is usually incidental, an air compressing plant is almost a foregone conclusion and it is more convenient to do work in waterbearing rock under compressed air. This is particularly the case where the cover of rock is thin or at the approach to the point where the tunnel will run out of rock into soft and waterbearing ground.

18. Ventilation Necessary.—If blasting is done under compressed air in a full rock face the volume of compressed air to be delivered to the working chamber will depend rather on the supply of an adequate volume of air to the men at work than upon anything else. This matter is discussed at greater length in Chap. XI. The conclusion was reached that an allowance of 2,000 cu. ft. of free air per man per hour was safe and reasonable and this volume should be supplied unless it can be shown without doubt that a less volume has no ill effects. If the explosive gives rise to particularly bad fumes, more may be required. It is a matter for experiment in each case.

(*A*-2) EXCAVATION IN DRY CLAY

19. Shield Tunneling in Dry Clay.—The early development of shield tunneling was carried out in London where about 100 miles of deep level tunnels have been built for the rapid transit system. Most of these tunnels were built through the clay underlying the greater part of that district. The running tunnels are of fairly small diameter, from 11 ft. 3 in. to 13 ft. 6 in. outside. The stations range from an outside diameter of 22 ft. 6 in. to 32 ft. with short lengths up to 36 ft. 9 in. and afford examples of tunnels of large diameter in this material.

20. London Clay.—The London clay is a dense and compact material, dark blue or gray in color and of remarkably uniform texture and composition. It is impervious to water and tunnels are driven through it freely without the use of compressed air, as far as keeping the face dry is concerned. It has been a common practice to use light air pressures when passing under or close

to heavy or important buildings to prevent or minimize the earth movements. The clay, although dense and massive, is divided into large masses by thin cracks, known as "backs" by the miners. These cracks have a roughly vertical direction and polished surfaces. They tend to produce slides of ground when opened up on a face and the ground tends to be quite "heavy" when the area of the face is at all large. In common with most other clays it swells after exposure to the air. Headings driven through this clay, which have been closely timbered with sills, posts and caps and braced with dimension timber may become practically closed after standing a few months. It is common to find, when a large section of tunnel has been excavated by hand and timbered, as for example a shield chamber, that the weight has been enormous. It is what miners call a treacherous ground. It looks easy, but it is not. It has to be treated with respect and an opening in it must be lined as quickly as possible. These characteristics make it an ideal field for the tunnel shield and it is the ground where the first development of the method took place on a large scale. The first example of the modern type of shield driven tunnel, namely the Tower Subway (E-2), was driven through the blue clay of London.

21. Methods of Excavating in Clay.—In the first tunnels, driven by shield through the clay the full face was excavated by the miner's pick for a length of one ring of the lining, which was of cast iron. The shield was pumped or screwed ahead into the space so cleared for it, the cutting edge merely trimming or paring off any small irregularities left. The ground was capable of standing without support until the shield was moved ahead.

22. Excavating with "Piles."—In the 11 ft. 3 in. diameter tunnels of the City & South London Railway (E-3) a marked improvement was introduced. This consisted of driving a heading some 6 or 7 ft. high and 4 or 5 ft. wide 6 to 8 ft. ahead of the shield. The heading is timbered with 4-in. caps and posts. When the shield is ready to be shoved, wooden "piles" or stakes about 3 ft. long by 4 in. square with a chisel point at one end are put in place around the cutting edge of the shield. The butts rest on the shield diaphragm and the chisel points in small pockets picked in the clay. Before the shove is started a few of the timber sets of the heading are knocked out and a rough breasting is thrown across the heading in advance of the furthest point to which the piles will reach at the end of the shove and a plank

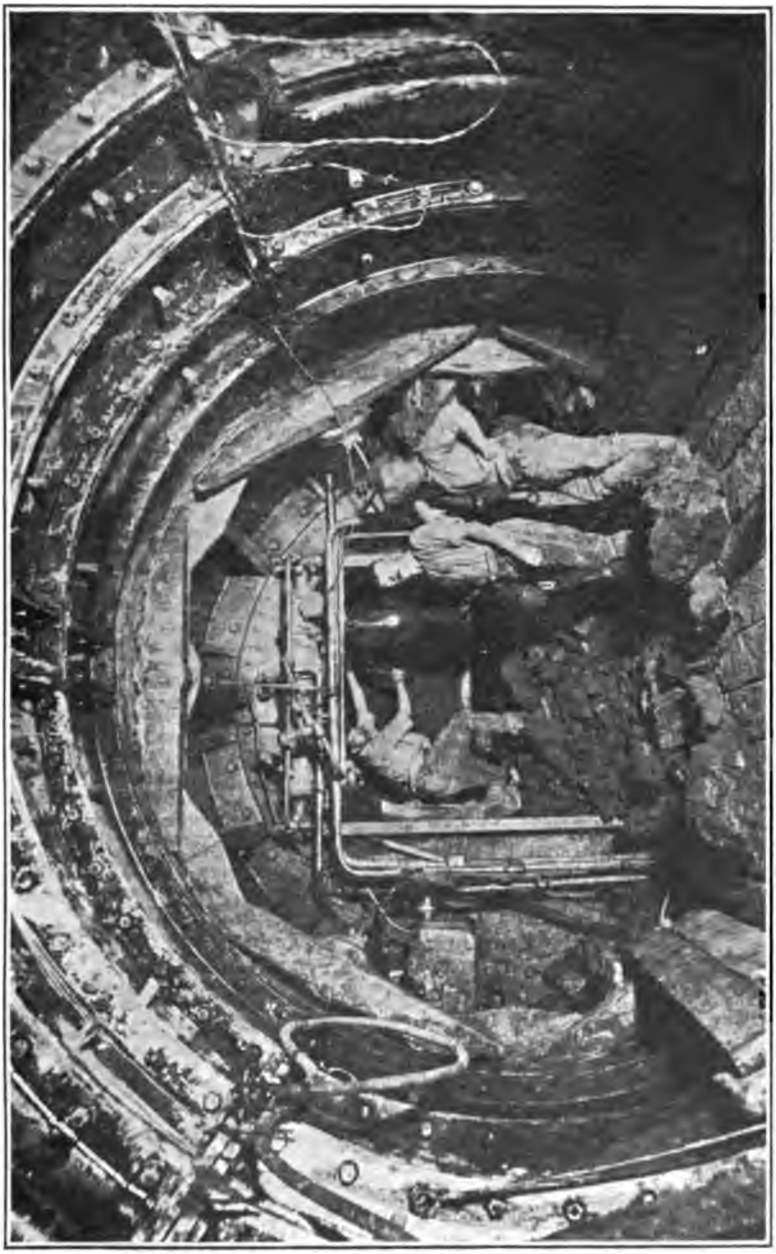


FIG. 108.—Small shield in London clay. Central London Railway (E-9).

platform is laid from the bottom of the heading into the shield and through the shield into the working floor of the tunnel. The hydraulic power is admitted to the jacks and the shield forced ahead. The shield presses the piles into the clay around the heading and breaks it down so that it is piled up on the platform in the bottom of the shield. The breasting across the heading prevents the loose clay from filling the heading to its face. After the shove is over the broken clay is loaded into cars and removed. All there remains for the miners is to trim up the excavation so that the cutting edge at the next shove has no more to do than to pare off chance lumps. The work of excavating the heading goes forward without interruption except that the men are withdrawn from the heading, as a matter of precaution, during the actual shove. Figure 108 shows a shield in London clay just after the shovel has been finished and the rams drawn back to make room for the next ring. The pile of loose clay is seen lying across the mouth of the heading and extending back through the shield. Two men can be seen in the length ahead of the shield, one trimming down the ground. Two more men are in the heading.

23. Increase in Rate of Progress.—The result of this method is to double the rate of advance. Copperthwaite (p. 99) says that a moderate rate of advance with a tunnel of 11½ ft. diameter would be 11 ft. 8 in. per 24 hr., while without the heading and piles the progress would be 5 ft. It is natural that the use of the heading and piles will increase the speed, first, because the face is divided into two stages so that more men can work at one time, and second, because at least 50 per cent, and possibly 75 per cent, of the excavation is done by the hydraulic power of the shield, which is much more effective than the miner's pick and is done simultaneously with the forward move of the shield.

24. Importance of Speed.—The matter of speed is important. Not only does the cost of the tunnel decrease rapidly as the speed of its driving is increased, but the faster the work of opening up the ground and erecting the lining the less the movements of the earth and the chance of causing settlements and damage.

25. Excavation in Large Shields.—In a large shield for station tunnel in clay the same process is followed. It is a common custom to drive the running tunnels through first, as this reduces the excavation to be done with the large shield and, more important still, reduces the area of, and consequently the pressure

on, the face. Piles are used, as with the smaller shields. Their efficacy is not so great owing to the greater solid surface of face. The shield is divided into floors and compartments as described in the Chapter on shields. The face jacks are used to support the face. The excavation is trimmed back by hand after each shove and the vertical face held by breast boards, strutted from the shield framing. The face jacks are kept pressed against the face continuously. After the face has been set forward between the various platforms and strutted from the shield as described the ground is broken down in front of the face jacks, which are immediately pushed forward again to support the face. The struts to the shield can be removed after the face jacks have been set forward and when the shield is shoved these jacks are forced back by the greater pressure of the shield jacks, maintaining during the shove their own full pressure against the face. In a shield of 32 ft. diameter the number of piles used will be over one hundred and the broken clay will be piled up on each platform floor to be cast thence into the muck cars. See Fig. 109.

26. Important Points for Large Shields.—The important points regarding these shields are (*a*) to have ample face jack power, (*b*) to have ample propelling jack power on the shield, (*c*) to divide the face of the shield in such a way that approximately an equal volume of excavation has to come from each pocket, (*d*) to design the shield so that it cannot distort. Some of the large shields used in London had one or other of these faults with consequent loss of time and increased expense.

27. Mechanical Excavators in Clay.—Of late years further improvements have been made in the clay tunneling shields. It is clear that by substituting mechanical appliances for the hand work of the miner a great gain in speed may be made. Several designs have been made and tried. The most successful is that invented by John Price of the contracting firm of Price and Reeves, London.

28. Price's Excavator.—The details of this machine have been described in Chap. IX. The operator must be competent and wide awake. He must not feed too hard into the ground, overstress the mechanism, and cause undue stresses on the completed tunnel lining, neither must he feed forward so slowly that time is lost. Great care is needed in the guidance of such shields. The advance is very rapid, consequently any error in driving

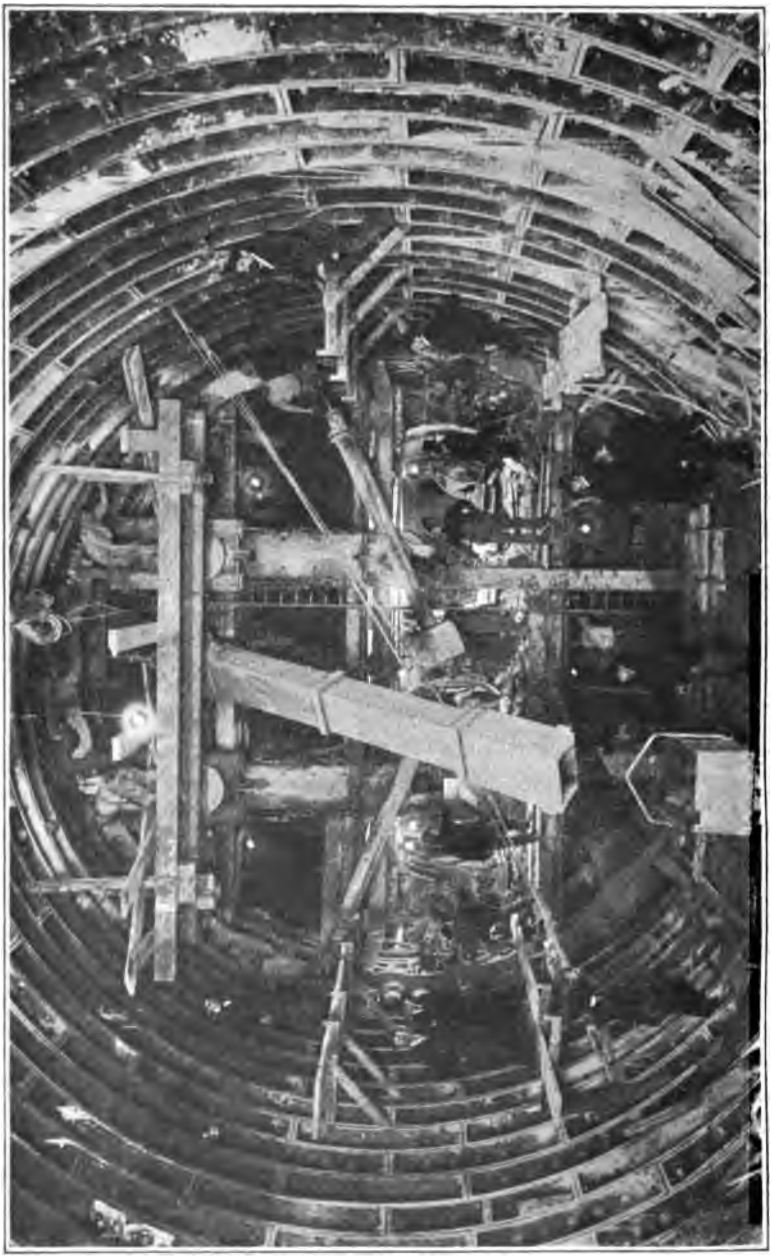


FIG. 109.—Shield 32 ft. diameter in London clay. The City & South London Railway (E-10) Angel Station, Islington.

rapidly mounts up. On the Rotherhithe pilot shield (E-17), 12 ft. 6 in. outside diameter, a shove for a 20-in. ring including all excavation, was 20 min. The early shields of this type were not driven well to line or gradient and Dalrymple-Hay states (*Proc. Inst. C. E.*, vol. 175, p. 216) that on one piece of work 25 per cent, and on another 10 per cent, of the finished work had to be altered to correct excessive deviation. By using careful methods on later work as much as 170 ft. of tunnel have been built in one week "without a single ring being off line or level by more than half an inch." The greatest advance on record is 185 ft. of 12 ft. 6 in. tunnel driven in one week. These rotary cutters have not been applied to any shield larger than 12 or 13 ft. They are designed especially for use in clay and reach their highest efficiency in that material. The pilot tunnel of the Rotherhithe tunnel, however, was driven through a mixture of materials, including a layer of rock, with one of these machines with complete success.

29. Reason for Using Shield in Dry Clay.—In clay that will stand like rock and will not swell no shield is needed. In dry clay of the nature of London clay, however, which has a tendency to swell when exposed to the air, the shield method is a great assistance in driving a tunnel, because it makes it possible to proceed without large and lengthy exposure of the ground.

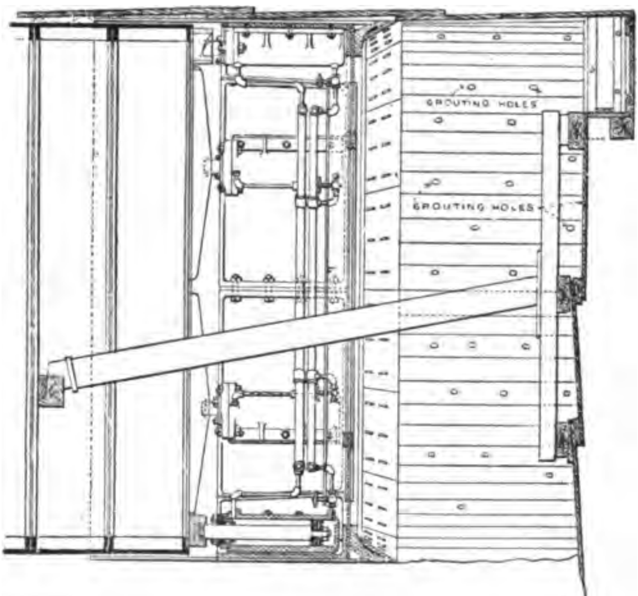
(*A*-3) EXCAVATION IN WATERBEARING GROUND

30. Excavation in Waterbearing Ground.—When the ground is waterbearing the work may be carried out in compressed air. The effect of the compressed air is to drive back the free water, provided the pressure is large enough. If the ground is so stiff that the air cannot escape through it and if the pressure of the air is not so high that it can displace the ground, the result of the action of the compressed air is to establish a condition of the ground as though it were non-waterbearing. Consequently, if the ground, when the free water is expelled or held back is cohesive enough, the work of excavation may be carried out in a manner similar to those described in the preceding paragraphs. Headings in advance should be used with extreme caution because a slight change in the consistency of the ground may change radically its capacity for self-support.

31. Excavation in Open Waterbearing Ground.—The methods used in open waterbearing ground vary with the size of the tunnel, the design of the shield and with the specific nature of the ground. Various methods will be described in the following paragraphs.

CITY AND SOUTH LONDON RAILWAY (E-3) and (E-10)

32. The Assisted Shield.—In the year 1888 during the work on the City & South London Railway built by Greathead as the pioneer of the net-work of deep level rapid transit tunnels which traverse London, some stretches of open waterbearing



Scale, ½ inch to 1 foot.

FIG. 110.—The assisted shield in water bearing gravel. The City & South London Railway (E-10). (From *Proc. Inst. C. E.*, vol. 123.)

gravel were met, although for the most part the work was in London clay. The shields were designed for use in clay and were of the type described in Chap. IX. This gravel needed support, not only on the vertical face but also around the circumference. When it was encountered the tunnel was put under air pressure and the work carried forward in the following way (see Fig. 110). "A small heading was driven at the top in

advance of the shield, stout poling boards being used to support the top, resting at one end upon the forward end of the shield; the heading was then widened out and the polings continued until about three-fourths of the circumference and the whole face had been poled." (Greathead, *Proc. Inst. C. E.*, vol. 123, pp. 66–67.) The whole surface was grouted with lime to reduce the escape of air. When the excavation for a ring length was done the support of the face, which had been propped temporarily off the front of the shield, was carried through the opening in the shield by means of stretchers the rear ends of which butted against a cross timber which, in turn, was supported against the flanges of the finished lining. The shield was then shoved, the skin of the shield sliding inside the circumferential polings. After the ring of lining had been erected the process was repeated.

33. Disadvantage of Method.—The value of the shield as a protection against an inrush of water or ground is lost by this method because of the stretchers which pass through the shield during the shove. This risk is real as may be seen from the accident that happened in Melbourne. A tunnel was being driven here by this method in open waterbearing ground. A blow occurred and owing to the impossibility of closing the shield the tunnel was flooded and every man inside the air lock killed. The assisted shield method, as it is called, should be used only where a short stretch of open ground is met on work otherwise in dry ground.

34. Water Trap.—For shields in open waterbearing ground a water trap construction as described in Chap. IX removes the dangers connected with the use of an open shield.

Waterloo and City Railway (E-8)

35. Hooded Shield.—In the year 1894 the Waterloo and City Railway was built through open waterbearing ground. H. H. Dalrymple-Hay was the resident engineer. After several months of work with the Greathead type shield using the assisted shield method, Dalrymple-Hay reached the conclusion that an improvement was possible and proceeded to put his ideas to the test. He designed the first "hooded" shield (see Fig. 111). The cutting edge was extended 2 ft. around the upper three-quarters of the circumference and this projecting hood formed a cover under which the miners could work. It allowed the gravel

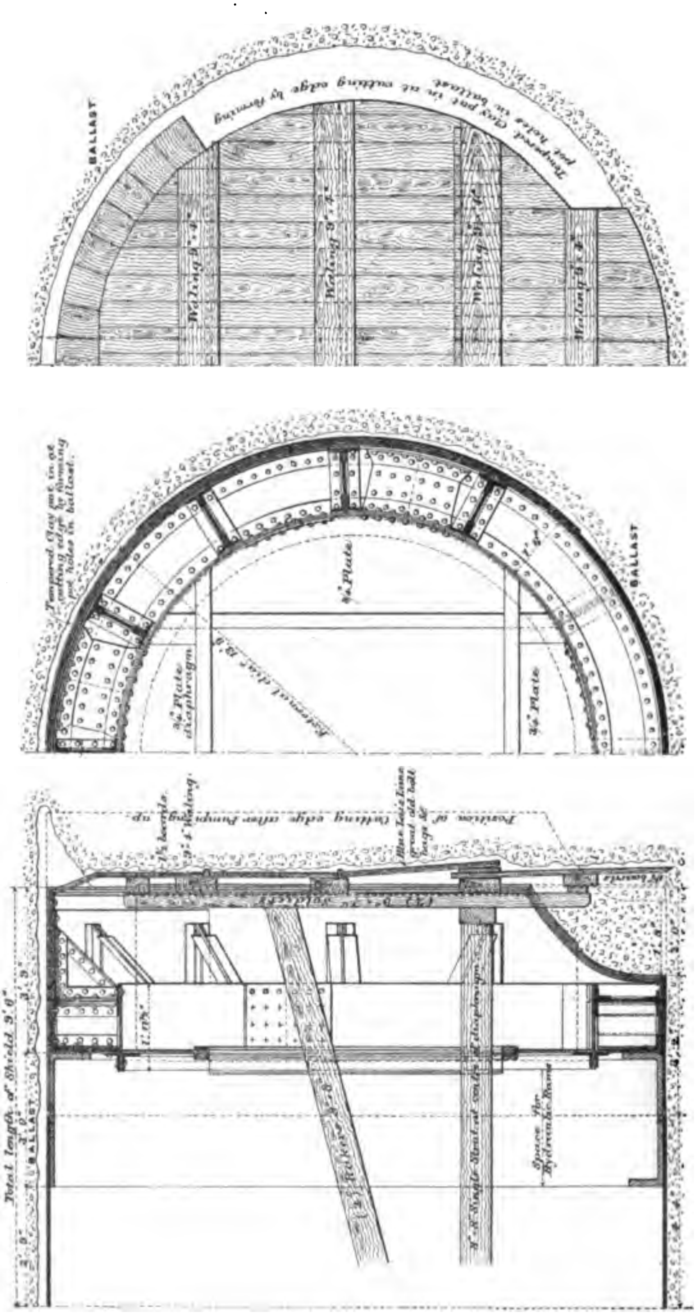


FIG. 111.—Hooded shield. Waterloo & City Railway (E-8). Method of work in gravel (or "ballast"). (From *Proc. Inst. C. E.*, vol. 139.)

to be removed entirely from the bottom and the shield to be shoved without undue pressure on the jacks and without fear of the lower part of the cutting edge being run unwittingly into boulders.

36. Clay Pockets.—Dalrymple-Hay made another noteworthy step, by using tempered clay instead of the poling boards around the cutting edge. This clay was placed in pot-holes raked out in front of the hood. Beginning at the highest point of the circumference a miner, armed with a "timber-dog," or large hooked spike, rakes out a hole from 12 to 15 in. wide and 22 or 24 in. long and fills the hole immediately with tempered clay. Another like hole is then raked out alongside the first one and filled with clay and this is repeated until a ring of clay has been formed immediately in front of and reaching about 2 in. above the hood. While each pot-hole is being made the air escapes freely, but when the clay stopping is put in the hole is made air tight at once. At the end of the shove the hood is buried completely in the tempered clay. Since the friction between the clay and the gravel is greater than between the clay and the shield a layer or skin of tempered clay is left outside of the skin of the shield as the latter advances. This layer of clay prevents excessive loss of air and supports the ground until the grouting can be done. The saving of compressed air by this method is important.

37. Support of Face.—Where the clay pockets were used the face was supported by timbering in the usual way. The breast-boards were vertical and held by walings strutted back from the shield diaphragm. After the whole face had been caught up in this way uprights, or "soldiers" were set against the walings and stretchers taken back from the soldiers to a cross-beam set across the finished tunnel lining behind the shield. The temporary stretchers to the shield diaphragm are struck and the shield is ready to shove. The operation is shown in Fig. 111. The raking out and "claying up" of the pot-holes is done at the same time as the timbering of the face. Sometimes the face polings are grouted or clayed up to lessen the escape of air.

38. Tendency of Hooded Shield to Dive.—The hooded shield in gravel has a strong tendency to dive, that is, it will stick its nose downward in spite of strong upward leads. It is customary to use timber or steel skids under the shield to keep it to gradient. This tendency is a serious nuisance and much attention must be paid to its prevention or correction.

BLACKWALL (E-7)

39. Shuttered Shields.—In the Blackwall tunnel shield a new departure was made in the design of shields for work in open gravel. This tunnel has an outside diameter of 27 ft. It crosses the Thames at London through beds of open gravel, is 3,116 ft. long and the maximum depth from highwater to tunnel invert is 80 ft. The minimum natural cover was 5 ft. of gravel directly under the river. The maximum air pressure was 35 lb. on the gauge. The contract was let to S. Pearson and Son in the year 1891 and the work was handed over complete to the City in 1897. The engineers were Binnie, Baker and Greathead whose resident engineers were David Hay and Maurice Fitzmaurice. The contractor's superintendent was E. W. Moir.

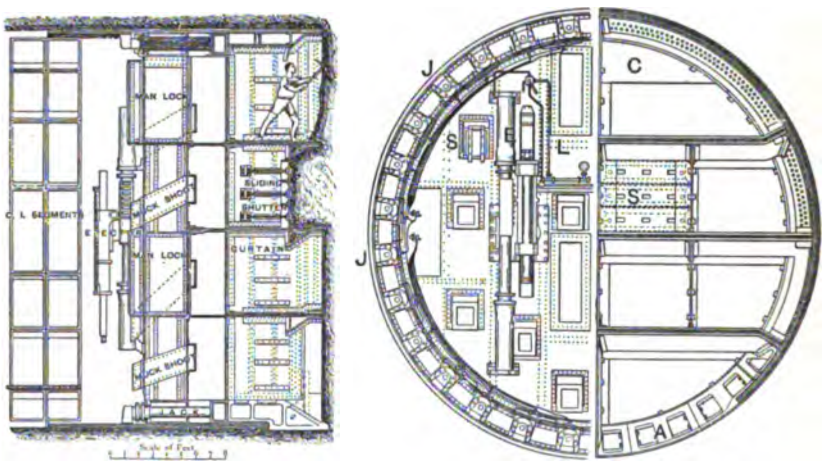


FIG. 112. The Blackwall Tunnel shield (E-7). (From *Journal of Soc. of Arts,* May 15, 1896.)

40. Blackwall Tunnel Shield.—The shield is shown in Fig. 112. It had two diaphragms. The rear diaphragm was 6 ft. 8 in. from the rear end of the shield tail and the front diaphragm was 3 ft. in front of this. These diaphragms were closed except for four air locks, two between the bottom and middle floor and two above the top floor, and twelve muck chutes, one in each pocket. Each of these chutes and air locks had rubber faced doors and could be closed, the intention to keep a higher air pressure in the working face than in the tunnel itself. It was

thought that not only could this be done but also a higher air pressure could be used in the lower pockets than in the upper. As a matter of fact this was not done and as stated in Chap. V it is difficult to see how it could be done.

41. Sliding Shutters.—The most remarkable feature of the shield was the "sliding shutters" which were provided over the face of the working pockets as described in Chap. IX.

42. Excavating in Front of the Shutters.—The excavation was always done from the top shutter down, in each pocket. The method varied according to the nature of the gravel and whether the air pressure was high enough to keep the ground dry. It might be so in the upper pockets and not in the lower ones. Under favorable conditions the gravel might be shoveled out from the top of the shutters, or a shutter might be drawn back and the gravel be scooped out between that and the next one below it. In very coarse gravel and under unfavorable conditions the sliding doors closing the small openings in the shutters were opened and the gravel raked out through the holes. Great care was taken to open as small an area as possible and each shutter was screwed tight to the ground as the gravel was removed.

43. Shoving the Shield.—The shield was not shoved the whole length of a ring at a time. Sometimes a few inches only at a time could be gained. The progress varied from 5 ft. in the worst week to 20 ft. a week when practice had been gained and confidence acquired. The number of hydraulic jacks for propelling the shield was originally twenty-eight. Each jack was 8 in. in diameter and had a 4-ft. stroke. In driving through the sand and gravel by the method described it was found that the shoving force was not enough and six more jacks of 10-in. diameter and shorter stroke were added. The maximum hydraulic pressure used was 6,170 lb. per square inch or 5,790 tons when all the jacks were working at full pressure.

44. Clay Blanket.—In the gravel under the river itself the cover was as little as 5 ft. 6 in. for a distance of about 150 ft. A clay blanket, 150 ft. wide and 15 ft. thick was placed on the river bed here. Without this blanket it is open to doubt whether the tunnel could have been built by the shield method. For days the top of the shield was in the clay blanket itself; the natural bed had come down through the shield.

45. Blows.—The tunnel air pressure was regulated to agree with the hydraulic head at the top of the shield so as to minimize

the risk of a blow. Nevertheless, two or three serious blows did happen and twice the tunnel was flooded in a few minutes to a depth of 7 or 8 ft., the men escaping with great hazard. The clay blanket sank into the hole caused by the blow.

46. Work in Bottom Pockets.—As the hydrostatic head at the bottom was about 13 lb. per square inch higher than at the top, the compressed air did not dry the lower part of the face. An enormous flow of water came through the gravel at the bottom.

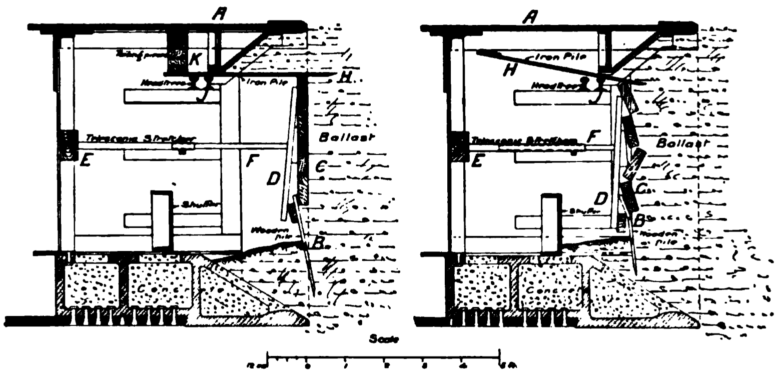


FIG. 113.—Blackwall Tunnel (E-7). Method of work in bottom pockets in wet gravel (or "ballast"). (Courtesy, of *W. C. Copperthwaite.*)

The sliding shutters were not used in the bottom pockets and the method of work used there is shown in Fig. 113. A combination of horizontal piles in the roof of the pocket with horizontal breasting below was used in these pockets. The horizontal breast-boards were held against the ground by telescopic stretchers which slid back as the shield advanced. This allowed the gravel to be cleared away up to the cutting edge, a thing not possible with the shutters. Perforated tunnel segments were used in the invert of the tunnel at intervals to relieve the inflow of water at the face. Jets of high pressure water and small shots of dynamite were used sometimes to shake up the ground. A man probed in front of the cutting edge to discover any boulders which might damage the cutting edge.

47. Progress Made under River.—It took 54 weeks to traverse the 1,220 ft. from the shaft on the one shore to that on the other, an average advance of 22 ft. 6 in. per week.

Baker Street and Waterloo Railway (E-15)

48. Small Shuttered Shield, Baker Street and Waterloo Railway.—The successful completion of the Blackwall tunnel, (E-7), driven through ground which, by ordinary mining methods, might be considered too difficult and dangerous even to be attempted, was a large step forward for the shield method. A year after its completion, in 1898, another tunnel was started under the Thames, also through the waterbearing gravel. There were two tunnels, each 13 ft. in outside diameter, with a maximum depth from highwater to invert of 70 ft. The shields were designed by Dalrymple-Hay and are shown in Fig. 114. It is seen that a series of hinged and sliding shutters was provided on the plane of the forward hood and covering the entire face to within 3 ft. of the invert. Each shutter was in two independent parts divided by the middle upright stiffener of the shield.

49. Shutters Discarded.—It was soon found in practice that these shutters were not suited to the size of the shield or to the ground to be penetrated or to both these in combination. The progress attained by them was slower than by the timbering methods. Soon after entering the gravel the top shutters became distorted. Since it was thought a poor practice to mix the method at the face by using timbering in the top and shutters below and since the progress with the shutters had been slow, they were removed and the method of timbering down the face was used.

50. Face Support by Struts through Special Openings.—By the method used on the City and South London Railway (E-10) and on the Waterloo and City Railway (E-8) (see par. **32** and **37**) the face had been supported during the shove by stretchers through the shield opening. In the Baker Street and Waterloo shield, as modified after the shutters were removed, the stretchers were carried through special openings. Two pairs of steel struts were provided. They consisted of steel tubes 5½ in. in diameter and 7½ ft. long. The forward end gave a bearing against the face walings and the rear end bore an adjustable head by which the strut could be tightened against a cross beam ("byatt") wedged against the tunnel lining. The struts passed through openings cut in the shield diaphragm. Leather sleeves were fitted close around the struts to render the joint partly air tight. This arrangement made it possible to advance the shield

with the diaphragm closed and increased the safety of the work. See Fig. 64.

51. Method of Supporting Face.—The breast boards were set

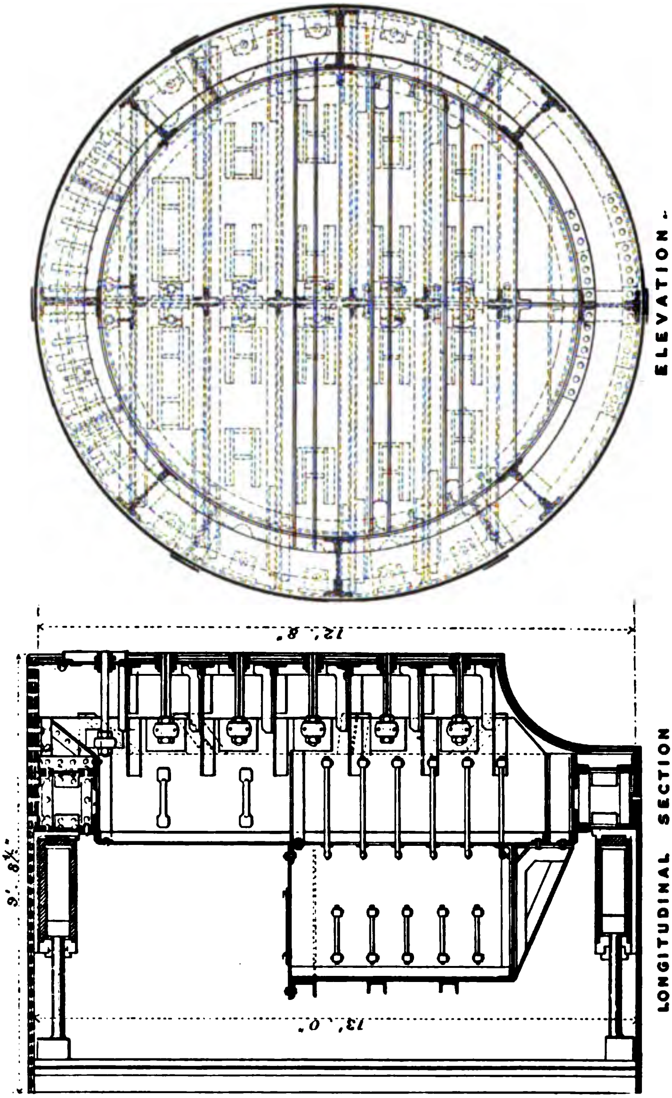


Fig. 114.—The Baker Street & Waterloo Railway (E-15) shield. (From *Proc. Inst. C. E.*, vol. 150.)

sometimes horizontally and sometimes vertically, as might be most convenient under the varying conditions of the ground. The "pugged" or tempered clay was placed around the shield

periphery as on the Waterloo and City Railway tunnels. The face boards were pugged liberally also to keep down the loss of air.

52. Adjustment of Air Pressure.—Several blows occurred although care was used to adjust the tunnel air pressure to the varying heights of the water in the river (the tidal range at London Bridge is about 21 ft.). "The blow-off of the air receiver was regulated automatically by a float on the river which carried a vertical board having an inclined channel bar groove attached to it. The groove constrained a roller which moved horizontally as the board rose and fell with the tide and varied by its movements the position of the fulcrum of the loaded valve-lever, thus varying the pressure according to the hydrostatic head" (*Proc. Inst. C. E.*, vol. 150, page 38).

53. Progress.—An advance of 5 ft. in 24 hr. was the usual progress.

Rotherhithe (E-17)

54. The Rotherhithe Tunnel Shield.—The Rotherhithe tunnel, with an outside diameter of 30 ft., is the largest tunnel driven by shield under compressed air across a waterway up to the present year, 1922. The construction of this tunnel occupied the period between 1904 and 1908. The chief engineer was Maurice Fitzmaurice and the contractors the firm of Price and Reeves. The shield was designed by the contractors and differed widely from that of the Blackwall tunnel. No shutters were fitted. Face jacks, 5 in. in diameter and of 30 in. stroke were arranged in pairs in each compartment, of which there were sixteen. In each compartment there was a water trap, made of a hanging diaphragm of steel plate with its lower edge about 3 ft. above the floor and 4 in. below the upper edge of another diaphragm which rose from the floor about 3 ft. behind the hanging plate. There were 40 shield jacks for propelling the shield, each with a diameter of 9 in. and a stroke of 3 ft. 6 in. The working pressure was 6,720 lb. per square inch, giving a total forward thrust of 8,500 tons. The shield is shown in Fig. 115. The total weight of the shield was 425 tons.

55. Ground Penetrated.—This tunnel passed through a series of roughly horizontal layers or bands of blue clay, mottled clay, sand and shelly clay, rock, pebbles and sand. The serious difficulties afforded at Blackwall were not present here.

56. Comparison with Blackwall Shield.—The shield was of vastly simpler construction than the Blackwall type. A tunnel shield is an instrument of brute force rather than of delicate persuasion. Simplicity combined with strength should be the key-note of its design.

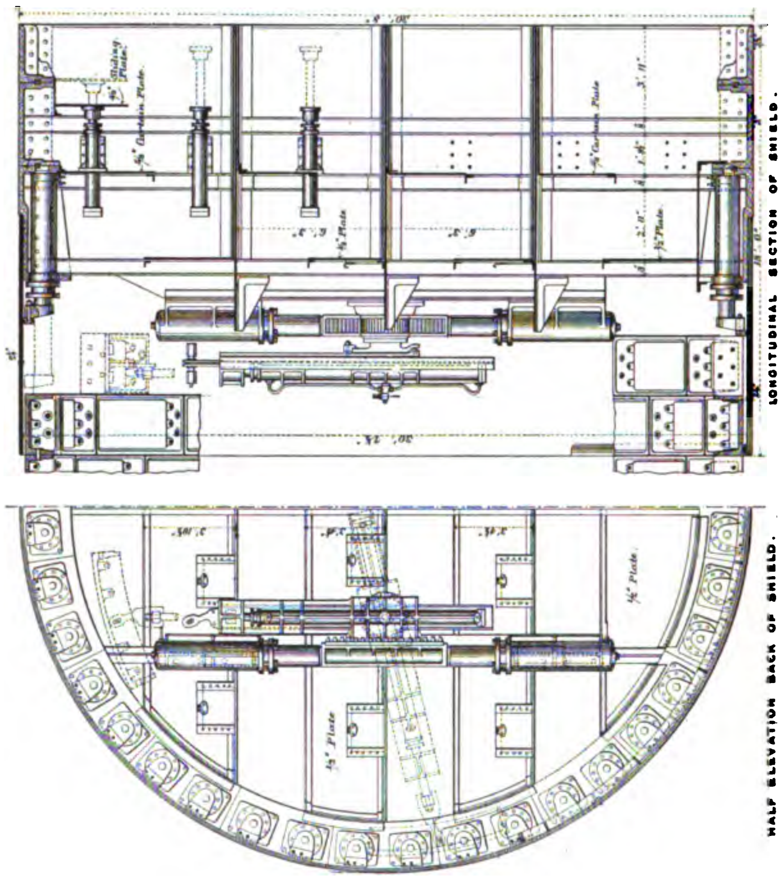


FIG. 115.—The Rotherhithe Tunnel (E-17) shield. (From *Proc. Inst. C. E.*, vol. 175.)

57. The Pilot Tunnel.—The Rotherhithe tunnel is noticeable for the fact that the contractor decided to drive a pilot tunnel ahead of the main bore in order to explore the ground. The pilot was 12 ft. 6 in. in diameter, driven with a rotary cutter shield of the Price type, and lined with cast iron. The pilot was started from the shore shaft on the north bank of the river and was stopped when 150 ft. from the south shaft which then had not yet been sunk. It was driven, therefore, 1,420 ft. Its

top was about 2 ft. below the top of the main tunnel. The pilot was started on Oct. 12, 1905 and stopped on Jan. 22, 1906. It was in action, therefore, 103 days, counting Sundays and holidays and the average progress was 13.8 ft. per day. The air pressure varied from 12 to 21 lb. per square inch. The time required to make a shove for one ring, 20 in. long, was about 20 min. in clay and 45 min. in hard ground. A bed of rock from 3 to 5 ft. thick overlaid with clay and sand and underlaid with sand and pebbly gravel delayed, but did not prevent the use of, the rotary cutter.

58. The Main Tunnel, under River Progress.—The main tunnel was started on Feb. 17, 1906 from the same shaft as the small tunnel and arrived at the south bank shaft on Nov. 21, 1906. The distance was 1,570 ft. 6 in. and the time elapsed 278 days. The average daily advance was 5.65 ft. The maximum advance in 24 hr. was 12 ft. 6 in. and the maximum in one month 267 ft.

59. Clay Blanket Not Needed.—Clay was kept in barges in readiness to place over the tunnel in case of a blow but it was not needed. The minimum cover was 8 ft. The clay bed of the river was so impervious to air that only a few bubbles were to be seen.

60. Methods on South Approach in Gravel.—Such difficulties as were met on this work did not occur under the river itself but in driving up the approach gradient on the south shore. The tunnel here is under private property and in gravel, below the plane of high water, for part of the distance. In such ground the breasted face was allowed to come back into the shield as this advanced, the cutting edge being forced into the gravel. Under these conditions all the jacks came into use under a pressure of 4,500 to 5,600 lb. per square inch. The average progress was almost the same as that under the river.

Pennsylvania Railroad, East River (A-19)

61. Pennsylvania Railroad Tunnels at New York.—The 23 ft. diameter tunnels of the Pennsylvania Railroad extension into New York City, built between 1904 and 1909, involved two crossings of the Hudson, or North, River and four of the East River. Sand and gravel were met in both rivers, but to a far greater extent on the East River than on the Hudson River.

62. Pennsylvania East River Tunnels, The Shields.—The chief engineer of the East River tunnels was Alfred Noble

and the contractors S. Pearson and Son, the builders of the Blackwall tunnel. There was a strong resemblance between the Blackwall and the East River shields. The main features of the Blackwall shield were reproduced here, including the

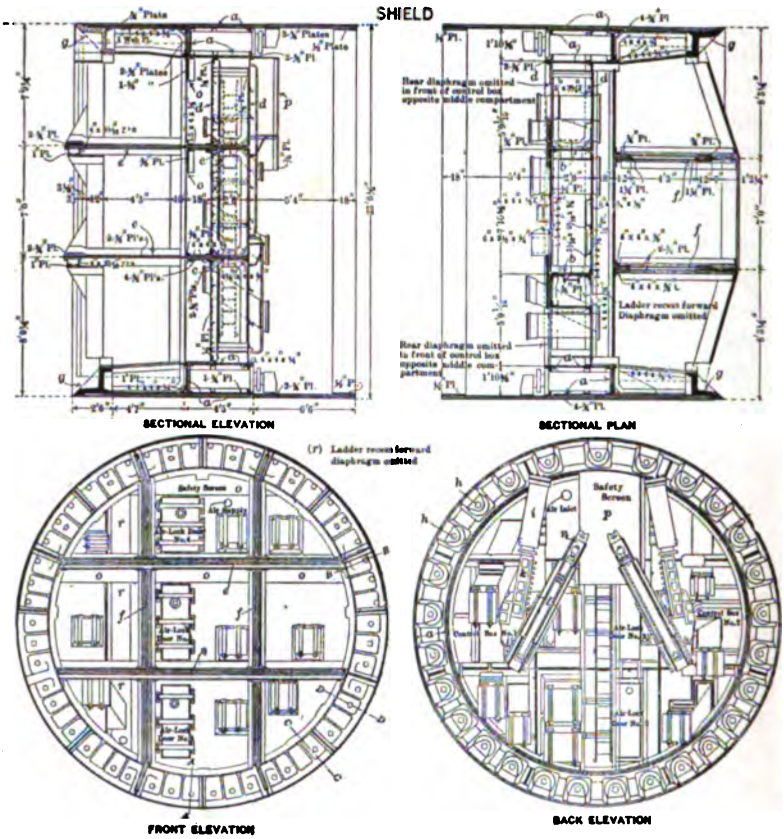


FIG. 116.—The Pennsylvania Railroad East River Tunnel, New York (A-19) shield. (From *Trans. Am. Soc. C. E.*, vol. 69.)

double diaphragm, the arrangement for keeping a higher air pressure in front of the diaphragm, the closed muck chutes and man locks, the bead on the tail and the sliding shutters for loose gravel. The shield is shown in Fig. 116, which shows the shutters clearly.

63. Modifications of Shield.—On the East River work the gravel was so unlike that at Blackwall that after a good deal of

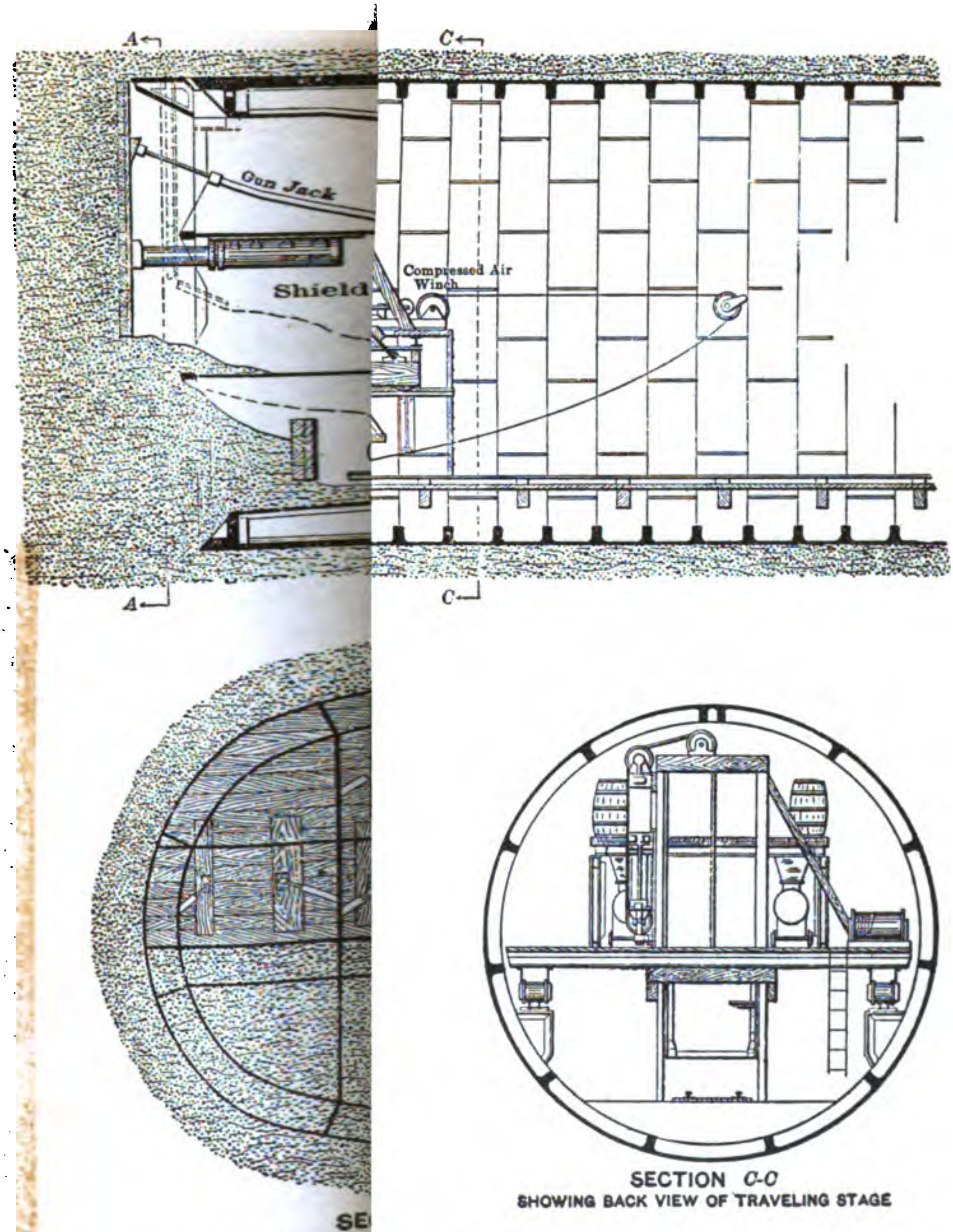


FIG. 117.—Shi . *Am. Soc C. E.*, vol. 68.)

(*Facing Page* 270.)

tunnel had been driven with their aid, but with fairly frequent blows, the shutters were removed and the work carried out by poling the roof and breasting the face. The tendency was always toward simplification. One part after another of the original shield was removed. Japp says (*Trans. Am. Soc. C. E.*, vol. 69, pp. 45–46): "The most satisfactory arrangement, in any type or mixture of types of material found under the river, was the bare shield with fixed hood projecting 3 ft. in advance of the cutting edge for about two-fifths of the circumference, and no extension floors except those formed by sliding timber extensions which could readily be replaced if damaged. These sliding timber floors were built of two 9 by 9-in. timbers in each pocket, decked with 3 in. planking, held down to the floor at the rear end by 8-in. cross timbers propped from the floor above and back-propped to the bulkhead. These sliding platforms were called cantilevers and were used also for supporting the poling boards of the roof. Braces (known as "guns") consisting of a 2½-in. pipe, filled with cement grout, sliding inside a 3-in. pipe, and gripped with set-screws were used for bracing the breasting boards. As the shield moved forward the set-screws were adjusted to give enough friction to hold the breasting boards tight while the guns telescoped on themselves. In the same way the cantilever timbers were adjusted as to friction by wedges between the bearing timbers and the cantilevers."

64. General Method of Work in Loose Ground.—The final method developed on the East River for working through loose open ground is shown in Fig. 117. The face was mined out to the front of the hood and breasted down to a little below the floor of the top pockets. In the middle tier the earth took its natural slope on the floor. Toward the rear of the bottom pockets it was held by stop planks. The air pressure was held at about hydrostatic head at the middle of the shield so that the ground in the lower pockets was wet and flowed under the pressure of shoving the shield.

65. Keeping to Line and Gradient.—While no particular difficulty was met in keeping to the desired line, the usual trouble with regard to keeping to gradient was met. In some cases the cutting edge of the shield had to be kept from 4 to 8 in. higher than the finished grade line of the tunnel. As in all these cases the constantly varying nature of the ground made it most hard to determine in advance how the shield should be pointed.

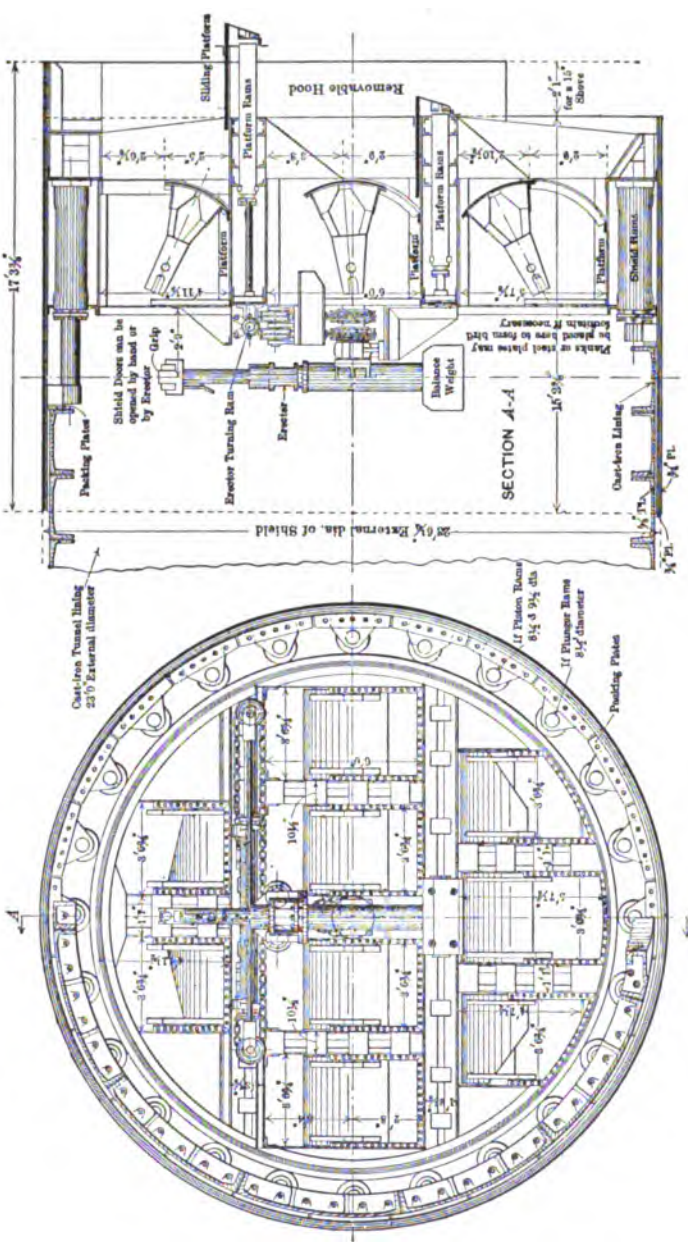


FIG. 118.—Pennsylvania Railroad Hudson River Tunnels (A-18), New York. The shield. (From *Trans. Am. Soc. C. E.*, vol. 68.)

66. Jack Pressures.—On an average the shields were shoved by ten or twelve of the bottom jacks with a pressure of 4,000 lb. per square inch. As the plungers were of 9-in. diameter the average total force on the shield was 2,800,000 lb. Where the shutters were used it would take over 6,000 lb. per square inch on all the 27 jacks so that the total forward thrust required was 10,300,000 lb.

67. Progress.—By the method outlined 4,195 linear ft. of tunnel were driven by four shields in 120 days, an average of 8.74 ft. per day per shield.

PENNSYLVANIA RAILROAD, HUDSON RIVER (A-18)

68. Pennsylvania Railroad Hudson River Tunnel Shield.—The chief engineer for the tunnels under the Hudson River of the Pennsylvania Railroad was Charles M. Jacobs, and the contractor was The O'Rourke Engineering Construction Company. The shields used are shown in Fig. 118. The design was worked up in the engineer's office and adopted by the contractor.

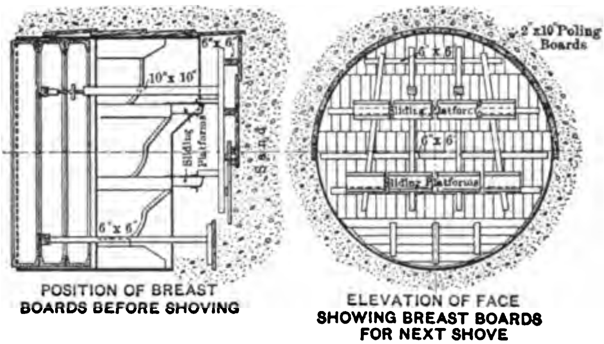


FIG. 119.—Work in waterbearing sand. Pennsylvania Railroad Hudson River Tunnels (A-18). (From *Trans Am. Soc. C. E.*, vol. 68)

69. Comparison with East River Shield.—The shield is a simpler one than the East River type. This is reflected in their weights. The structural portion of the East River shield weighed 185 tons and that of the Hudson River shield 135 tons, a difference of 37 per cent. The hydraulic fittings for the Hudson River shield weighed 58 tons additional.

70. Method of Work in Sand, Hudson River.—The system of timbering used is shown in Fig. 119. The ground was excavated

2 ft. 6 in. (the length of one ring of the lining) ahead of the cutting edge. The roof was held on longitudinal poling boards resting on the outside of the shield at their back end and on vertical breast boards at the forward end. When the upper part of the face was dry the ground there was held by vertical breast boards braced from the sliding platforms and through the shield doors to cross timbers in the tunnel. The lower part of the face which was always wet was held by horizontal breast boards strutted through the lower shield pockets to cross timbers braced across the tunnel.

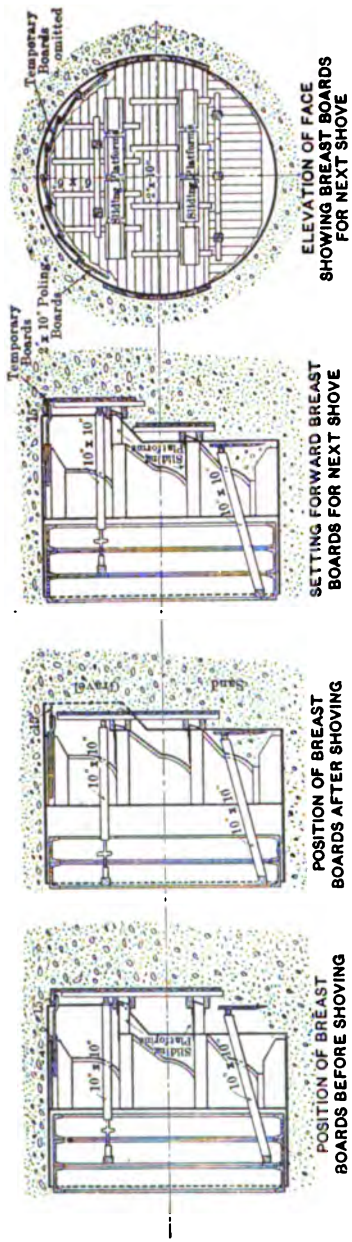


Fig. 120.—Work in waterbearing gravel. Pennsylvania Railroad Hudson River Tunnels (A-18). (From *Trans. Am. Soc. C. E.*, vol. 68.)

71. Method of Work in Gravel, Hudson River.—When the upper part of the face was in gravel, making it impossible or inconvenient to put in the longitudinal poling boards or the vertical breast boards another system had to be used. In that case the excavation was carried only 15 in. (half a ring length) ahead of the cutting edge and the longitudinal polings were replaced by transverse boards supported by pipes which were placed in holes provided in the shield diaphragm to take breasting struts which had been designed but not made. The pipes acted as cantilevers and were in two parts. A 2½-in.

pipe was wedged tight into the holes and smaller pipes slid inside them, like the guns used on the East River shields. After a small section of the ground had been excavated a board was placed against it, one of the pipes drawn out under it and wedges driven between it and the board. These breastings were kept below the level of the overhanging hood, so that, when the shield was shoved the boards would come inside of the shield. The boards were braced also by vertical posts from the sliding platforms. The upper part of the face was held by horizontal breast boards braced from the sliding platforms by upright soldiers. The lower part of the face was caught by "piling" (vertical breast boards) braced to the tunnel through the lower doors. Sometimes two rows of piling were used, though one was usual. The system is shown in Fig. 120.

72. Shoving the Shield.—Although the breasting was only 15 in. ahead of the hood the shield was advanced 30 in., the ground around the cutting edge of the hood being scraped away by men working bars in the place from which the temporary breast boards at the circumference had been removed. The back pressure on the sliding platform jacks, when their exhaust valves were partly open, offered a good resistance and held the face up as long as the movement of the shield continued.

73. Escape of Air.—There was an enormous escape of air while working in the sand and gravel although large quantities of straw and clay were used in front of the boards to cut down the loss. The joints of the iron lining were pugged up with clay also. As more air was being lost than the power plant could supply to two tunnels, the expedient of working the two tunnels in turn was adopted. That is, one tunnel was under compressed air and being advanced while the other was under normal air and at a stand-still. The one under normal air acted as a drain to the one being driven. Work in each tunnel was alternated. When one tunnel got 150 ft. ahead of the other it was stopped, the air taken off and the other started up. In this way the capacity of the power plant was made equal to the demand and it may be a useful expedient to remember when confronted with a similar problem. It is of value only when the open gravel portion is short in comparison to the work as a whole so that the expense of an air compressing plant of a capacity great enough to cover all the tunnels at once in the open gravel would not be warranted.

74. Progress Attained.—On these tunnels in sand and gravel the average progress was one ring of 2.5 ft. length in 10 hr. and 15 min., or 5.85 ft. in 24 hr.

Sand and Gravel, General Conclusions

75. The Shield.—The shield should be strong and simple in design. Elaborate or ingenious devices are usually a handicap. The value of sliding shutters is doubtful. They have been tried on several shields but have been discarded on all except on the Blackwall tunnel (E-7) shield and it is possible that equal progress might have been made here without the shutters. Furthermore, they did not prevent blows of a serious nature. Air lock devices on the shield have been tried and discarded; they look fine in theory to inexperienced minds but do not work in practice. On the other hand, it is not wise to go so far toward simplicity as to leave the shield absolutely unprotected in case of a blow. It should not be necessary, as often it has been, to support the face through the shield doors to the lining behind. Plenty of face jacks should be provided and spaced so that one is available for the support of the face at any point. They should extend beyond the front plane of the cutting edge when at their furthest reach. Each jack should have pressure enough to resist the external pressure that may come upon it. They should be heavy enough so that they will not be exposed to being bent or damaged. Face jacks near the outer circumference of the shield are useful. The cutting edge should be made strong and should be in sections that can be replaced if damaged. A hood in sand or gravel saves lumber when used in connection with clay pockets, otherwise the shield is probably better off without it. Sliding hoods that could be driven into the ground in advance of the shield would be excellent, but the difficulty is to prevent them being damaged. Plenty of propelling jack power should be provided.

76. Method of Attack.—The method of attack is a combination of mining methods and brute force. Mining methods are used to advance the excavation over as large an area of the face as possible. Where these methods fail the shield is pushed bodily into the ground with the hope of displacing what cannot be removed. The latter method is used where the danger of causing a blow prevents the air pressure from being raised high enough to

dispel the water in the lower part of the face sufficiently to permit excavation. It is plain that when the work is done in this manner the ground will flow not only from in front of the shield but also from below, producing the troublesome tendency the shield will have to get below its proper gradient.

77. Pilot Tunnel.—It seems that a promising method of driving a large tunnel in open waterbearing ground, where difficulty exists of excavating the lower part of the face, would be to run first a pilot tunnel of a smaller diameter as used on the construction of the Rotherhithe tunnel (E-17), but not at the top as it was done there, but at the bottom, with the invert on the same gradient as the main tunnel. This would take care of the excavation of the lower part of the main tunnel and permit the ideal of keeping the face under control even at the bottom. The main objection to this procedure would be the cost of the lining for the pilot tunnel, but the advantages gained would largely outweigh this objection.

(*A*-4) EXCAVATION IN MIXED GROUND

78. Mixed Ground.—By mixed ground is understood soft ground at the upper part of the face and rock at the lower part. This condition presents difficulties which will tax all the resources of the engineer and the tunnel man, because of the necessity of maintaining the support of the soft ground while the rock is being blasted out below.

Ravenswood Tunnels (A-8)

79. Description of Work.—Perhaps the first instance in which a tunnel shield was driven through a mixed face of rock and soft ground occurred on the Ravenswood gas tunnel which crosses from Manhattan Island to Long Island on the line of 71st Street, Manhattan, traversing the East River under Blackwell's Island. The tunnel was started on June 28, 1892 and was completed for operation on October 15, 1894. The engineer was Charles M. Jacobs. The tunnel has a total length of 2,516 ft. The outside diameter of the shield driven portion is 10 ft. 10 in. The tunnel roof grade is 109 ft. below high water on the Manhattan side and descends on a drainage gradient of one-half of one per cent to Long Island, where the roof is 122 ft. below high water. The

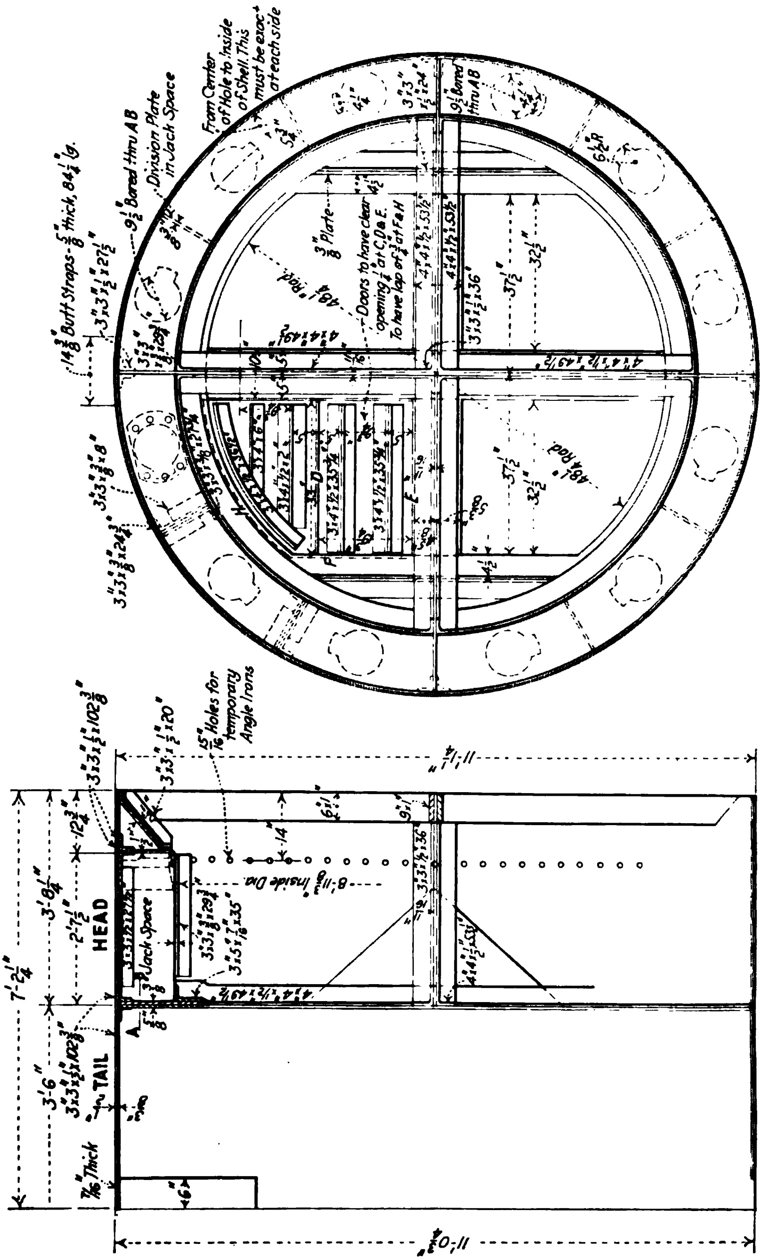


FIG. 121.—The shield, Ravenswood Gas Tunnel (A-8). (From *Journal of Assoc. of Eng. Societies*, May, 1895, vol. 14.)

minimum cover in the river is 41 ft. in the channel west of Blackwell's Island and the depth of water here is 70 ft.

80. Decomposed Seams of Rock.—It was expected that the tunnel was to be all in rock and the work was started by mining methods without shield and compressed air. Soon difficulties were caused by waterbearing fissures. Finally solid rock ceased and a soft feldspathic mass of soluble material was encountered. Air pressure was installed and the work continued under a gauge pressure of 48 lb. per square inch. After protracted struggle the contractor abandoned the work.

81. Shield.—It was decided to continue the work with forces organized and directed by the engineer and to adopt the shield method combined with a cast iron lining in order to get through the soft mass of material which blocked the advance. The shield is shown in Fig. 121. It was 11 ft. 0¾ in. in outside diameter and 7 ft. 2¼ in. in overall length. It was divided longitudinally in two portions. The tail portion, 3 ft. 6 in. long was built of two plates, the inner ⅜ in. thick, the outer ½ in. The cutting edge section was 3 ft. 8¼ in. long with skin plates of the same thicknesses as the tail. Each of these sections was fabricated in four quadrants for facilitating erection. The diaphragm separating the two sections was made of one ⅝ in. and one ⅜ in. plate, stiffened with angles. One plate was riveted to the tail section and the other to the cutting edge section. The two plates bolted together with butt straps united the sections. It is clear from Fig. 121 that there was a working platform on the horizontal diameter of the shield, and since there was a vertical middle frame in the diaphragm, the face was divided into four pockets. Two doors, hinged on the vertical partition were provided in each pocket, so that there were eight doors, hinged like ordinary doors or gates, by which the face could be closed. There were twelve 5-in. hydraulic jacks to propel the shield. They could carry a working pressure of 5,000 lb. per square inch, giving a total available forward thrust of 590 tons on the shield.

82. Work in Mixed Face.—In September 1893 a shield chamber was cut in the rock on the New York side and on Nov. 24, 1893 the shield was started under a pressure of 45 lb. per square inch. Almost as soon as the work was started the most difficult conditions of all on this work were met. The top of the shield was in soft black mud while there was a length of about 12 ft. of hard rock in the bottom, dipping at an angle of about 40 degrees

toward the Long Island shore. Blasting had to be done in the bottom pockets after the top had entered the soft mud. It was with the greatest difficulty that the bottom pockets could be kept clear of this mud. It was virtually impossible to hold it and several serious inrushes happened. These established direct connection with the river bed and live fish, crabs, mussels, boots, bricks and tin cans entered the tunnel. The air escaped in large volumes and caused a geyser in the river. On December 13th, the shield cleared the rock and entered a full face of undisturbed mud.

Hudson Tunnel (A-6)

83. Hudson River Tunnel, Hudson and Manhattan Railroad.—In the year 1902 work was re-started on the old Hudson River tunnel which had been begun by D. C. Haskin in the year 1874. The work was now initiated by W. G. McAdoo with C. M. Jacobs as engineer doing the work with his own forces. The description which follows applies to the tunnel which now forms the northerly one of the pair which crosses the Hudson River between Morton Street, New York and 15th Street, Jersey City, near the Hoboken terminal of the Lackawanna Railroad. This North tunnel had been driven, partly by Haskin and partly by Pearson, 3,916 ft. eastward from the New Jersey shaft and 160 ft. from the New York shaft. The gap remaining was 1,925 ft. At a distance of 136 ft. eastward from the shield abandoned by Pearson came a reef of rock which extended for a length of 750 ft. on the line of the tunnel. This reef had an upward slope so that while it was first met in the invert of the tunnel it rose gradually until the top of the rock was 16 ft. above the invert of the tunnel, which had an outside diameter of 19 ft. 6 in.

84. Jacobs' Report.—Jacobs, whose experience on the Ravenswood tunnel was of great value here, rendered a report in 1895 to the effect that the shield could be carried through the reef if an apron were added for the protection of the men when drilling the rock.

85. Work in Mixed Face.—The work was started on Oct. 22, 1902, using the old shield left by Pearson. By Nov. 29, 1902 an advance of 136 ft. had been made through the silt and the cutting edge had reached the rock. The situation was this. The rock in front of the shield, varying in height from one foot to

sixteen feet above the bottom had to be blasted away. Overlying the rock was a bed of soft silt. The depth of the water in the river above the silt was 60 to 65 ft. The method of work may be told in Jacobs' own words (*Proc. Inst. C. E.*, vol. 181, pp. 177–178): "The heading in front of the shield was enlarged and solidly timbered to form a working chamber for the purpose of attaching a steel apron just below the axis and extending across the shield and projecting 5 ft. beyond the cutting edge so that the men might have sufficient overhead protection in drilling the rock, and also to act as a material safeguard against the inflow of silt. This work of reconstruction occupied 47 days and was carried out under an air pressure of 42 lb. The alterations to the shield being completed on the 1st of February, 1903, progress was resumed with the shield partly in rock and partly in silt. The surface of the rock ledge was very irregular, in some places passing below the line of the tunnel and again above. When not in rock, the shield was forced ahead by the jacks without any workmen being in advance of the diaphragm, the material encountered being forced into the tunnel through one or more doors in the diaphragm. If the shield would not advance with a hydraulic pressure of 3,000 lb. per square inch on the jacks the pockets of the shield were excavated and rock and other hard materials found holding the shield were blasted away. This pressure on the jacks was determined as the safe thrust that the shield would withstand without damage. In view of the probable disturbance of the river bed which this blasting would involve, scows holding about 600 cu. yd. of clay were held in readiness to be dumped over the point of disturbance in case of a blow, which precaution proved to be well justified. Nevertheless, two serious blows, entailing the flooding of the tunnel did occur, but on dumping two scows over the break, the escape of air through the river bed was stopped, enabling the water to be blown out. The men succeeded in recovering the heading in 11 hr. and in 23 hr., respectively, from the time the blow occurred. The work of blasting the rock proceeded until the last few feet of the reef were reached, when the rock had now reached its highest point, 16 ft. above the bottom of the cutting edge, on the east side of the ridge. The silt at this point was in a semi-fluid state and five barges of clay had been deposited to reinforce it. Very great difficulty was encountered here due to the clay creeping through the shield doors and all efforts by poling and other mining

devices to hold the clay back far enough to enable the drillers to work were unavailing. An unusual method was then determined upon; namely to bake the clay by means of intense heat. Two large tanks were sent into the tunnel, filled with kerosene under pressure; five blow-pipes were attached to the tanks, and the fire from the blow-pipes impinged upon the exposed clay, until it became caked sufficiently dry and hard to prevent slipping. The time occupied in the application of heat extended over a period of 8 hr. and during this time water was played continually on

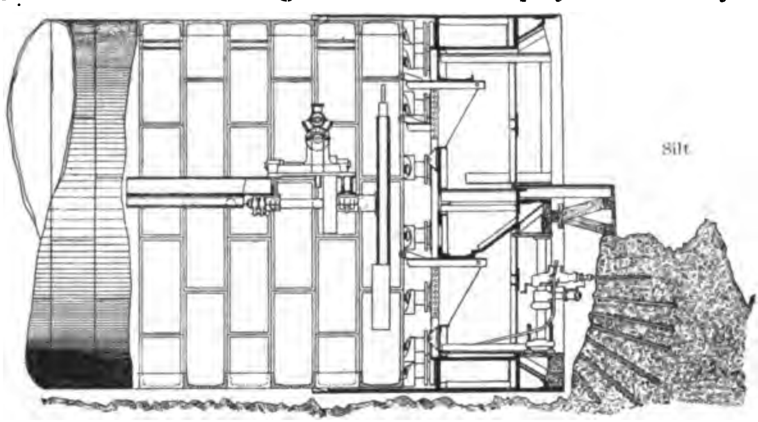


FIG. 122.—Work in mixed face. Drilling rock under protection of "apron." Hudson and Manhattan Railroad, Hudson River, New York (A-17). (From *Construction of Hudson and Manhattan Railroad* by *J. V. Davies*.)

the shield to avoid damage due to the high temperatures. This is believed to be the first time that soft material met with in tunneling under the bed of a river has been solidified by means of fire while working under an air pressure of 38 lb. per square inch. Seven days after passing this high point the rock disappeared and sand was reached." Figure 122 shows a longitudinal section of one of the shields of the Hudson and Manhattan Railroad, with rock in the lower part of the face and soft ground above.

PENNSYLVANIA RAILROAD, HUDSON RIVER (A-18)

86. Mixed Face Work on Hudson River Tunnels, Pennsylvania Railroad.—The shields of the Pennsylvania Railroad tunnels under the Hudson River were started in solid rock on both sides of the river. The rock disappeared on each side before the river bulkhead line was reached and consequently,

the top of the shield first ran out of rock and the condition was presented of a gradual lowering of the rock level and a steadily increasing proportion of soft ground in the face as the shield advanced. The work was done under an air pressure varying from 12 to 26 lb. per square inch.

87. Method of Work.—The general method of face support is shown in Fig. 123. When the surface of rock was first penetrated the soft face was held by horizontal boards braced from

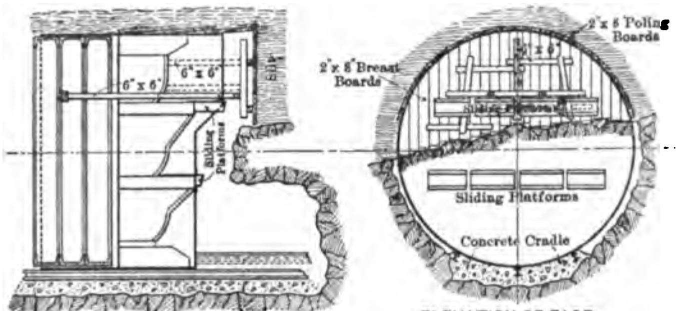


FIG. 123.—Work in mixed face (rock in bottom and silt above). Pennsylvania Railroad Hudson River Tunnels (A-18). (From *Trans. Am. Soc. C. E.*, vol. 68.)

the diaphragm until the shove took place. The braces were then removed and replaced by others as soon as the shove was over. As the area of soft ground in the face increased, the timbering took the form of a series of 2-in. poling boards resting on the top of the shield at their rear end and caught at the face on vertical breast boards. These were held by walings braced through the upper doors of the shield to the iron lining behind and also by the sliding platforms on the shield itself. The platforms were out as far as they would go before the shield was shoved. Just before the shove was started the exhaust valves on the face jacks were opened. As the shield went ahead the platform jacks exhausted and thus held enough pressure to support the face.

88. Rate of Progress.—The average rate of progress was 2.6 ft. per day of 24 hr. with three 8-hr. shifts.

PENNSYLVANIA RAILROAD, EAST RIVER (A-19)

89. Mixed Face, East River Tunnels, Pennsylvania Railroad. On the East River tunnels of the Pennsylvania Railroad some

difficult work was encountered with rock in the lower part of the face and boulders and coarse sand above. The escape of air was great and it was necessary to excavate the soft ground over the rock, before the rock was blasted, to a point beyond that to which the rock had to be blasted, to allow the shield to be shoved. Two forms of hood were tried in this ground, the sliding hood and the fixed hood. With the fixed hood it was necessary either to excavate and support the loose ground far enough in front of the hood to enable the shove to be made or else to ram the hood bodily into the ground. The sectional hood was designed to avoid this difficulty.

90. Sliding Hood.—The sectional sliding hood consisted of steel poling boards lying on the outside of the shield and advanced, independently, by screws. In using this type the top segment, or poling, was forced forward by the screw as far as possible into the undisturbed material. Enough material was removed from underneath and from in front of the section to allow it to be screwed forward again and this process was repeated until the section was far enough advanced for a shove. The same was done with the sections on each side of the top one. When two or three sections had been screwed forward the face at the forward end of the sections was caught by a breast board braced from the shield. One by one the segments were worked forward and gradually the whole of the soft ground face sheeted. At times polings were placed over and beyond the extended hood segments to make room for a second shove. This is shown in Fig. 124. When the shield was shoved the nuts on the screw rods were loosened and the sections of hood telescoped back on the shield. The method did not turn out well as the unequal movements of the top and bottom of the shield brought transverse stresses on the hood sections which they could not stand.

91. Fixed Hood.—With the fixed hood, polings were used on the roof and sides and the face was supported as with the sliding hood. The polings were of 2-in. oak or maple, 6½ ft. long. To advance the face, the top board of the previous breast was taken out and the material cautiously worked out for the length of the poling. This was then set with its rear end on the hood and its leading end forced as far as possible into the undisturbed ground. When two or three polings were set a breast board was placed. After several polings were in place their forward ends were

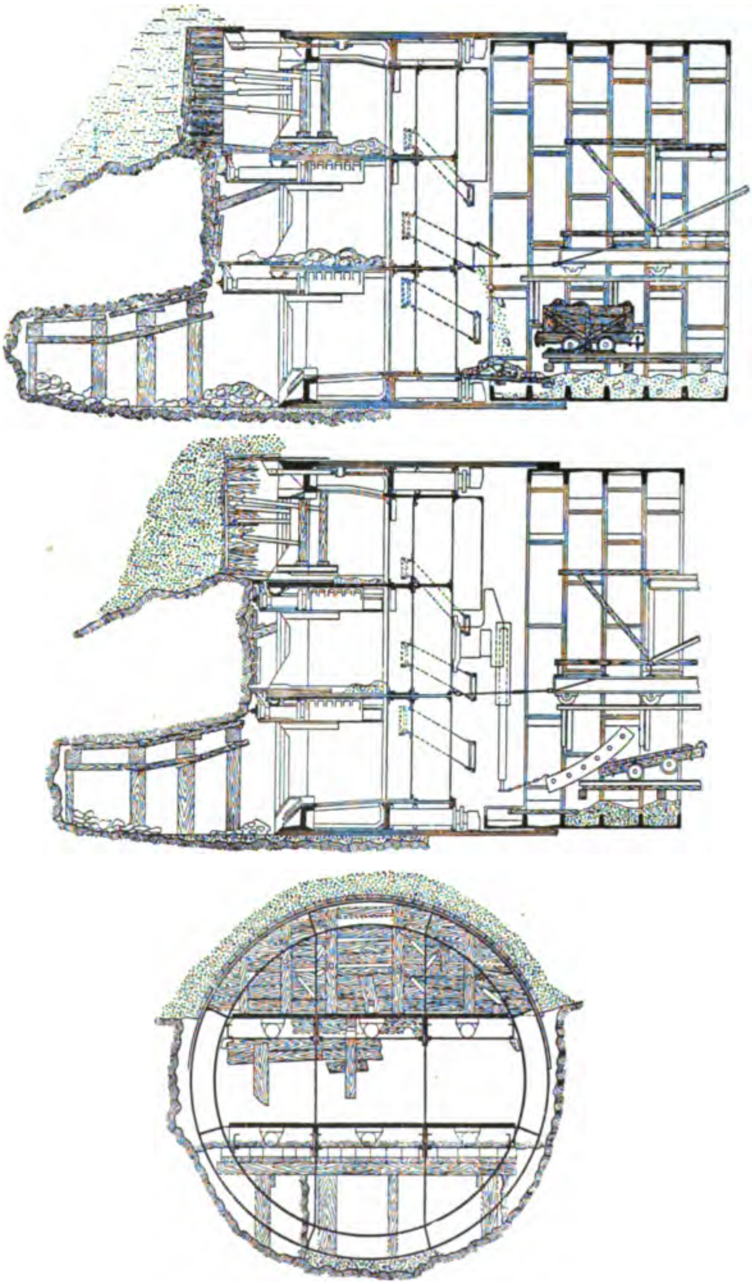


FIG. 124.—Work in mixed face with sliding hood. Pennsylvania Railroad East River Tunnels (A-19). (From *Trans. Am. Soc. C. E.*, vol. 68.)

supported by a cantilever attached to the hood (see Fig. 125). In this way all the soft ground was removed down to the rock surface and the roof, sides and face sheeted with timber. The roof and side polings were lost and left behind. The fixed hood made it possible to set the face from 7 to 8 ft. ahead of the cutting edge. This was enough for two shoves and was the standard method, although many faces were set for one shove only.

92. Blasting.—When the rock part of the face was sound enough and high enough a bottom heading was driven 20 or 30 ft. ahead of the shield, and a concrete cradle placed. This work was carried out independently of the work in the soft ground above. The rest of the rock was taken out by firing top and side rounds into the bottom heading after the soft ground had been excavated. Great care was used to prevent disturbance of the timbering and not to break the rock away below the breast boards. If either of these happened a run was certain. It was found that the rock could be drilled from columns set in the bottom pockets of the shield while the work was going on in the soft ground above. The drillers were protected by timber platforms, or aprons, built out from the floors of the pockets above.

Mixed Ground, General Conclusions

93. General Conclusions.—It is apparent that in a face with soft ground at the top and rock at the bottom, the difficulties are about the same as those met in a full face of open ground except that the trouble connected with excavating the wet and flowing ground at the bottom of the tunnel in the latter case has been replaced by the greater one of removing the rock without disturbing the loose ground above. The procedure at the upper part of the shield is about the same, but special precautions must be taken to prevent the shoring of the face from being displaced by the blasting below. When possible it is advisable either to drive a bottom heading in the rock in advance of the soft ground excavation or to carry this out some distance ahead of the rock excavation, in other words, whenever possible blasting should not be done immediately below the breasting of the face. A shield hood which does not extend below the rock surface will assist in carrying the breasting ahead of the rock.

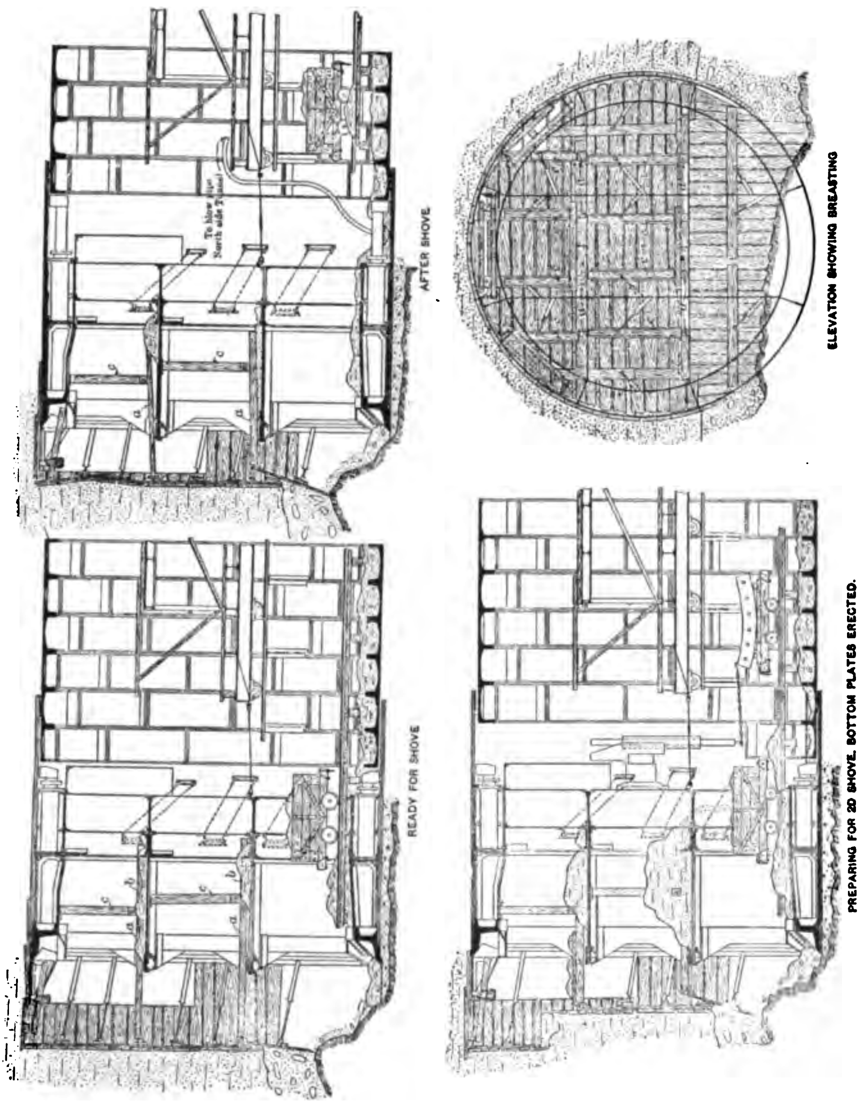


FIG. 125.—Work in mixed face with fixed hood. Pennsylvania Railroad East River Tunnels. (A-19). (From *Trans. Am. Soc. C. E.*, vol. 68.)

(*A*-5). EXCAVATION IN MUD

94. Character of Work.—Life holds no greater horror for the old fashioned miner than liquid or semi-liquid mud. This material is very heavy, that is, it brings enormous pressures on timbering set up to support it and to prevent it caving in, and at the same time it is so fluid that it runs through the slightest crevice. The old fashioned miner indeed had a difficult task before him in attempting to stem the flow of this material with his poling boards. By packing behind with straw, hay, manure, sawdust and similar materials and by opening the smallest possible area of ground at a time he was able, perhaps, to get along, but only at infinite difficulty and, of course, at enormous cost. The larger the tunnel the greater the difficulty and danger and it may be said that after a certain moderate limit of size was reached the old mining methods became prohibitive in time, risk and expense. On the other hand, the shield method makes this material about the easiest through which a tunnel may be driven. The highest rates of progress are made through mud with a shield, but its peculiar characteristics must be understood in order to avoid difficulties and delays.

Hudson River Tunnels (A-6) and (A-17)

95. The Hudson River Tunnel.—The first occasion in which a shield was used in mud was in the year 1890–1891 when an English company took over the work of Haskin under the Hudson River at New York, which had been abandoned in 1882. The engineers were Fowler, Baker and Greathead, whose representative in New York was W. R. Hutton. The contractor was S. Pearson and Son, represented by E. W. Moir.

96. Work of S. Pearson and Son.—The shield designed for this work was built in Scotland and is shown in Fig. 126. The tunnel was in soft Hudson River silt and much difficulty was found in driving the shield on the desired gradient owing to its strong tendency to dive. It was found unnecessary to excavate ahead of the shield. When the shield was forced ahead the mud squeezed through the doors so that all that had to be done was to load it on the muck cars. About 1,900 ft. of tunnel was built in this way in one year; a maximum advance of 72 ft. of tunnel, which was 19 ft. 6 in. in diameter, was made in one week. In

July, 1891, the work had to be dropped again on account of exhaustion of the funds.

97. Work of Jacobs.—In the year 1902 the project was revived by W. G. McAdoo with C. M. Jacobs as engineer. The

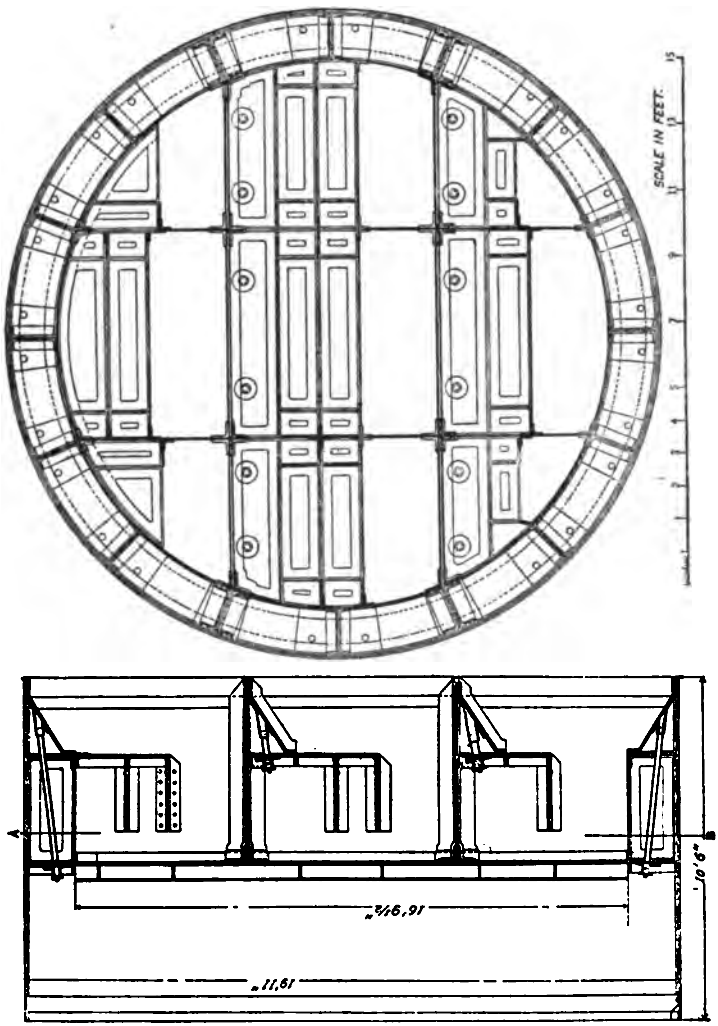


Fig. 126.—Pearson's shield for Hudson Tunnel (A-6). (From Simms' "*Practical Tunneling*.")

work was completed without a contractor. The Pearson shield was driven through a mixed face of silt and rock as previously

described and 17 new shields were built for the rest of the work. These were made to withstand the full pressure of sixteen 8-in. jacks under a pressure of 5,000 lb. per square inch.

98. "Shoving Blind."—Soon it was found that the shields could be shoved with all the doors closed, taking in no ground at all. This was known as "shoving blind."

99. Force Required.—With one of these shields, 17 ft. in diameter and 11 ft. 5 in. long, it was found that the shield began to move with 1,600 lb. per square inch on eleven 8-in. jacks. This is equivalent to a pressure of 3,900 lb. per square foot on the face area of the shield. At a pressure of 2,500 lb. per square inch on 11 jacks, equivalent to 6,000 lb. per square foot of face area, the movement was one-half inch per minute.

100. Volume of Silt Admitted.—Since the full force of 5,000 lb. per square inch on all sixteen jacks was equivalent to 17,000 lb. per square foot of shield face area there was ample reserve power for shoving blind and generally three or four of the upper jacks were not used. The discovery was made that better control was given, the shield was more easily steered, when some of the silt was allowed to come through the doors. It became the custom, therefore, to keep one of the doors open and to take in an average of 5 per cent of the volume occupied by the tunnel. This feature was more strongly marked in the case of the larger tunnels of the Pennsylvania Railroad driven a few years later through the same ground, as will be described in paragraphs **102** to **110**.

101. Progress Made.—On the Hudson tunnels—16 ft. 7 in. in outside diameter—built in this way, as much as 62 ft. of tunnel has been driven and lined in 24 hr. and 346 ft. in one week. The English company, eleven or twelve years before, had reached 72 ft. of 19 ft. 6 in. tunnel in one week. In their case a great deal more than 5 per cent of volume displaced by the tunnel had been taken in. Moreover, the cast iron lining used by the English company was based on the proportions used in London clay and was inadequate in strength under the pressures of the semi-liquid silt. The consequent distortion must have caused a good deal of trouble and delay in its erection and in the work which had to be done to keep it in shape after it had been erected.

PENNSYLVANIA RAILROAD, HUDSON RIVER (A-18)

102. Hudson River Tunnels, Pennsylvania Railroad.—The tunnels of the Pennsylvania Railroad under the Hudson River are 23 ft. in outside diameter. They cross the Hudson River between New York and Weehawken, N. J. on the line of 33rd Street, New York and were built in the years 1903–1906, under C. M. Jacobs as engineer. The total length of tunnels driven by shield was 12,255 ft. of which 8,000 ft. were in true Hudson River silt.

103. Silt on Landward Side of River Bulkheads.—Nearly one thousand feet of silt, representing the bed of the river before reclamation work had set the river bulkhead line out into what was once the tidal foreshore, were traversed under a cover of 50 ft. This material, under the action of compressed air, looked much like London clay. The shields were shoved through this ground under an air pressure of 20 lb. with all doors open taking in about 90 per cent of the full volume of displacement. When the air pressure was raised two pounds the silt became harder and the quantity which flowed in fell to about 65 per cent of the displacement. This at once caused a disturbance on the surface and a pronounced hump was caused in the railroad tracks over the tunnels at this point. The air pressure was dropped, therefore, to 16 lb. allowing the full displacement to come in.

104. Silt under River.—As soon as the shields crossed the river bulkhead and entered under the river the silt was found to be much softer than under land. It was like a fluid. The fluidity could be changed by varying the air pressure in the tunnel. When the air pressure was equal to the pressure of the overlying material, namely that of the water plus that of the silt, the silt was quite stiff and resembled a rather soft clay. When the air pressure was 10 to 15 lb. per square inch lower, it became so liquid that it would flow through a 1½ in. grout hole in the lining, in a viscous stream at a rate of from 10 to 15 gal. per minute, as soon as the plug was removed.

105. Shoving Blind.—When the first shield crossed the bulkhead line the doors were closed and the shield was shoved blind. At once the shield and the tunnel began to rise rapidly, notwithstanding that the heaviest possible downward leads were put on. The pressures induced in the silt by the forward movement of

FIG. 127.—Work in Hudson River silt. Silt flowing through middle; bottom pocket. Pennsylvania Railroad Hudson River Tunnels (A-18). (Courtesy of *Pennsylvania Railroad.*)

the closed shield caused the iron lining to rise two inches as soon as the shield left it. The lining was distorted also; the horizontal diameter decreased about $1\frac{1}{4}$ in. while the vertical diameter increased a similar length. These phenomena had not been expected and their cause was not clear. It was thought that it was due to the overhanging hood. The shield was stopped, the hood removed and the driving resumed. Things were no better and it was impossible to follow the downward gradient. The work was halted and the matter debated. Finally the chief engineer directed one of the shield doors to be opened and 50 per cent of the volume taken in.

106. Effect of Opening Door.—The effect was instant. The shield began to come down at once and it was soon necessary to close the door partially to reduce the volume of ground taken in, so that the tunnel should not get below grade.

107. Guiding the Shield by Regulating Volume Taken in.—It was found that a powerful aid in guiding the shield was given by the regulation of the volume of mud allowed to flow through the shield. If high, the shield could be brought down by increasing the volume of mud brought in; if low, by decreasing it. During the work in the silt the quantity of mud taken in at each shove was regulated according to the position of the tunnel and the nature of the ground at the point. The silt varied a good deal from place to place, being much softer in spots than the general run.

108. Method of Regulating the Volume Taken in.—To regulate the flow the bottom middle door was fitted with two steel angles, behind which were placed 6 by 6 in. timbers. This opening could be closed entirely or regulated to any size. The mud flowed into the tunnel in a thick stream as shown in Fig. 127. By regulating the rate of shoving the shield the mud could be made to flow just as fast as it could be shoveled into the cars.

109. Volume Taken in.—On these tunnels the volume taken in, regulated as described, varied from nothing to the full volume displaced. The average for the whole work was 33 per cent.

110. Progress.—The maximum advance of one shield in one month in silt on this work was 545.2 ft. The average time taken in the silt to advance the shield 30 in. which was the length of one ring, to clean up and load the excavated material and to erect the ring of iron was 3 hr. 26 min. made up as follows:

TABLE XXIII.—PENNSYLVANIA RAILROAD HUDSON RIVER TUNNELS ANALYSIS OF TIME TAKEN TO ADVANCE SHIELD AND ERECT ONE RING OF LINING IN SILT

Operation	Time taken		Percentage of total time for one ring
	Hr.	Min.	
Shoving and mucking	1	09	33.4
Erecting lining	2	05	60.8
Lost time	0	12	5.8
Total for one ring	3	26	100.0

111. Relation between Air Pressure and Depth of Tunnel.—In the silt the tunnel air pressure was kept lower than the hydrostatic pressure at the crown of the tunnel under ordinary working conditions. If it became necessary to excavate ahead of the shield as at the point where the shields met, the air pressure required was about equal to the aggregate pressure of the overlying water and silt.

112. Nature of Silt.—The silt acted as a fluid having a weight of 97 lb. near the surface and 106 lb. at the level of the tunnel. The further down from the bed of the river the firmer and the heavier was the silt found to be.

113. Influence of Diameter of Tunnel.—It will be noticed that the vertical height of the tunnel has a profound influence on the way the silt can be treated when a shield is driven through it. On the 16 ft. 7 in. diameter tunnels of the Hudson and Manhattan Railroad, it was enough to take in an average of 5 per cent of the displacement of the tunnel in order to hold adequate control over the shield. On the 23-ft. tunnels of the Pennsylvania Railroad through the same ground, an average of 33 per cent had to be taken in. If these two instances are considered as lying on a straight line curve, Table XIV shows the percentages of the displacement necessary to admit in tunnels of various diameters.

114. Fineness of Silt.—The solid particles in the mud forming the bed of the Hudson River are of extraordinary fineness. It is finer than Portland cement as may be seen from Table XV following.

TABLE XXIV.—SUPPOSED RELATION BETWEEN DIAMETER OF TUNNEL AND PERCENTAGE OF DISPLACEMENT NECESSARY TO TAKE IN WHEN IN SILT

Outside diameter of tunnel in feet	16	20	25	30	35	37
Percentage of tunnel displacement necessary to take in	0	19	42	65	90	100

TABLE XXV.—COMPARISON BETWEEN FINENESS OF PORTLAND CEMENT AND OF HUDSON RIVER SILT

Material	Percentage passing standard sieve	
	No. 100 sieve	No. 200 sieve
Portland cement	90	70
Hudson River Silt	97	83

This means that 97 per cent of the solid particles of this mud has a diameter of 0.0055 in. or less and that 83 per cent has a diameter of 0.0026 in. or less.

115. Water Content in Silt.—Samples taken in the tunnel showed a water content of 55 per cent by volume. At high tide the weight of the silt is greater than at low and the water content less. This points to the probability that the increased pressure at the top drives out some of the supersaturation water of the silt and brings the solid particles closer together.

116. Tidal Rise and Fall of Silt.—The conclusion reached in the previous paragraph is borne out by the fact that the silt, as a mass, rises and falls as the tide falls and rises. A tunnel embedded in the material is carried up and down with it as the tide falls and rises. There is no reason to assume that the tunnel moves in relation to the ground. In the Hudson River at the tunnel elevation, the amplitude of the tidal range of the tunnel is about 1/8 in. with an ordinary tidal range of 4 ft. in the river.

117. Angle of Repose of Silt.—The angle of repose was determined as being a little less than 3 degrees, by many hundreds of pressure gauge observations, at a time of from 3 to 6 months after the shield had passed. This fact has an important bearing on the stability of tunnels driven through this kind of ground. If the silt were a perfect fluid, the tunnel would be in equilibrium only when the weight of the tunnel lining were equal to the

weight of the displaced ground. If the weight of the lining were greater, the tunnel would sink; if it were less, the tunnel would rise. Generally the weight of the lining will be less than that of the displaced ground and the indicated buoyancy has given rise to much anxious thought as to a possible necessity of anchoring tunnels to prevent them from rising up into the waterway above. Although it is apparent from the behavior of the lining as described in par. **118,** that the silt during the construction period temporarily and locally will approach in character that of a fluid, it is also apparent from the evidence of the pressure tests as well as from the experience of tunnels already built, that the silt possesses some permanent resistance and that this resistance is sufficient to overcome the buoyancy of the tunnels already built. It is probable that the buoyancy of even lighter linings would not cause any rise because the existing tunnels remained for long periods of time after construction and erection of the cast iron lining without being subjected to the load of the interior concrete lining and did not show any definite tendency to rise. Definite proof does not exist, however, because this evidence may have been complicated by leakage. Until more knowledge has been gained it is probably advisable not to presume too heavily on the permanent resistance of the silt.

118. Distortion of Cast Iron Lining.—When driving through the silt the cast iron lining first became shortened on the horizontal diameter and correspondingly lengthened on the vertical. This action began as soon as the ring of iron was erected and continued for about two weeks. At the end of this period the distortion had reached an average value of 1¼ to 1½ in. The action then became rather suddenly reversed and the horizontal diameter began to elongate while the vertical began to shorten. This action went on slowly and continuously until the placing of the internal concrete lining stopped further measurements. In other words the second action continued for 30 months or so, at which time the iron had about come back to a true circle. If any distortion was present, the horizontal diameter was slightly larger than the vertical.

119. Suggested Cause of Distortion.—The above points to the following as being what probably happened. The angle of repose of the material at the level of the tunnel before the shield reaches it has some value which is more or less unknown, but which is at any rate as great as or greater than 3 degrees. The

shield comes along, driven blind or partly so, exerting a pressure which may be anywhere between three tons and eight tons per square foot of its face area. This work done on the silt breaks down its cohesion, as happens when a small lump of silt is rubbed in the hands, so that its angle of repose becomes zero for the nonce, and the material acts like a fluid of the specific gravity of the silt. The shield passes on. Slowly, gradually the silt returns to its normal state having an angle of repose of more than 3 degrees.

120. Earth Pressures Greatest at Initial Construction.—Since the deformations are greatest at the time of initial erection the forces at that time must be greatest. It is not the permanent conditions of stress, therefore, which the design must meet as much as the temporary stresses induced by the construction. These matters are covered in Chap. VII.

121. Influence of Quantity of Mud Admitted.—In par. **113** it was pointed out that the average percentage of the tunnel displacement which need be admitted through the shield in any given case depends on the diameter of the tunnel. The smaller the tunnel the smaller the percentage which can be admitted, and yet allow the shield to be kept to grade. It was shown in that paragraph that as far as conditions in the Hudson River mud are concerned it would be possible to control a 16 ft. tunnel without taking in any mud while a 37 ft. tunnel would require the full volume of tunnel displacement to be admitted. These figures cannot be taken as final, because the cases on which they are based are insufficient but they may be considered as illustrating the general tendency. The greater the percentage to be taken in the less the work done on the ground around the tunnel, the less the breaking down of the cohesion and the less the conversion into a fluid. Conceivably, with 100 per cent displaced volume taken in, its original structure would not be impaired or altered, and a condition would be presented rather of tunnel through clay than one through liquid or semi-liquid mud.

122. Example, Haskin's Work.—A confirmation of this view is afforded by the work of Haskin on the first Hudson River tunnel. Haskin had no shield and mined the ground out by hand, placing as a primary lining a flimsy structure of wrought iron plates connected by 3-in. angles. (See Fig. 127 *A*.) The vertical diameter of his tunnel was 22 ft. 6 in. and he succeeded in getting 1,540 ft. under the river. He had troubles from

earth pressures and plenty of them but he was able to proceed. If the mud had acted as a fluid he could not have gone a foot.

123. Effect of Volume Admitted on Progress.—It will be recognized, that the greater the proportion of displacement which has to be allowed to flow into the tunnel the greater and the longer the work of mucking in the tunnel will be, and consequently, the slower the progress. This must be given due consideration when making estimates of the probable time and cost of tunnels driven through mud.

FIG. 127 *A*.—Haskin's Hudson Tunnel (A-6). Some of his wrought iron lining plates uncovered during the construction of the uptown tunnel of the Hudson and Manhattan Railroad (A-17).

124. General Conclusions.—To drive a shield through mud may be easy work in a sense. A shield reaches its highest efficiency in such ground and progress is apt to be fast. The matter of guidance, however, is anything but easy. If he wants a tunnel that will give him credit the engineer will have to use all his skill and care from the moment the shield first buries its nose in the mud.

(A-6) EXCAVATION IN MUD WITH EMBEDDED OBSTRUCTIONS

125. Mud with Embedded Obstructions.—It occurs sometimes that the shield has to be driven through mud in which obstructions are embedded. These obstructions may be boulders, tree

trunks, piles or such matters. Their effect is to prevent the shield from being shoved through the mud without excavating ahead.

126. Method Used.—In such cases the obstructions have to be taken out one by one or piece by piece and the shield must be driven into a previously excavated chamber as in the case of tunneling in dry clay.

127. Rip Rap.—If the shield intersects a mass of rip rap filling which extends to the surface or nearly so a difficult situation is presented, because the interstices between the boulders afford a free exit for the air and the chances of a blow are imminent.

128. Precautions Necessary.—It will be found necessary to have an ample supply of puddled clay on hand and to use this freely to "pug up" the spaces between the stones as soon as they are uncovered. The stones must be removed cautiously one by one under an air pressure high enough to hold out the water and yet low enough to keep the chance of a blow to a minimum.

129. Escape of Air at Tail of Shield.—There will be an avenue for the escape of air presented by the clearance between the tail of the shield and the lining. This space must be closed with gunny sacks, clay or similar packing. While the shield is being shoved the difficulties will be increased largely. The movement of the shield displaces the packing. Men must be stationed to keep replacing the packing as quickly as may be and to pug up every opening which allows air to escape, the moment it shows itself.

130. Erecting the Lining.—After the shove has been made and the next ring is going in, the packing must be cleaned off the front flange of the last ring for the length of a segment of a new ring. As this segment is placed the packing will be replaced, but in the mean time there is an escape of air.

131. Unremitting Care Necessary.—It is only by the exercise of unremitting care and by grouting freely right up to the shield that one will get successfully through this material. Even with the use of all precautions blows will be more or less common and must be checked, if possible, in the early stages.

132. Piles.—When the obstructions consist of piles the situation is not so fraught with danger as the piles act as timbering. Each pile has to be cut away, as it is met, into short lengths which can be removed through the openings in the shield.

CHAPTER XIII

CONSTRUCTION (Continued)

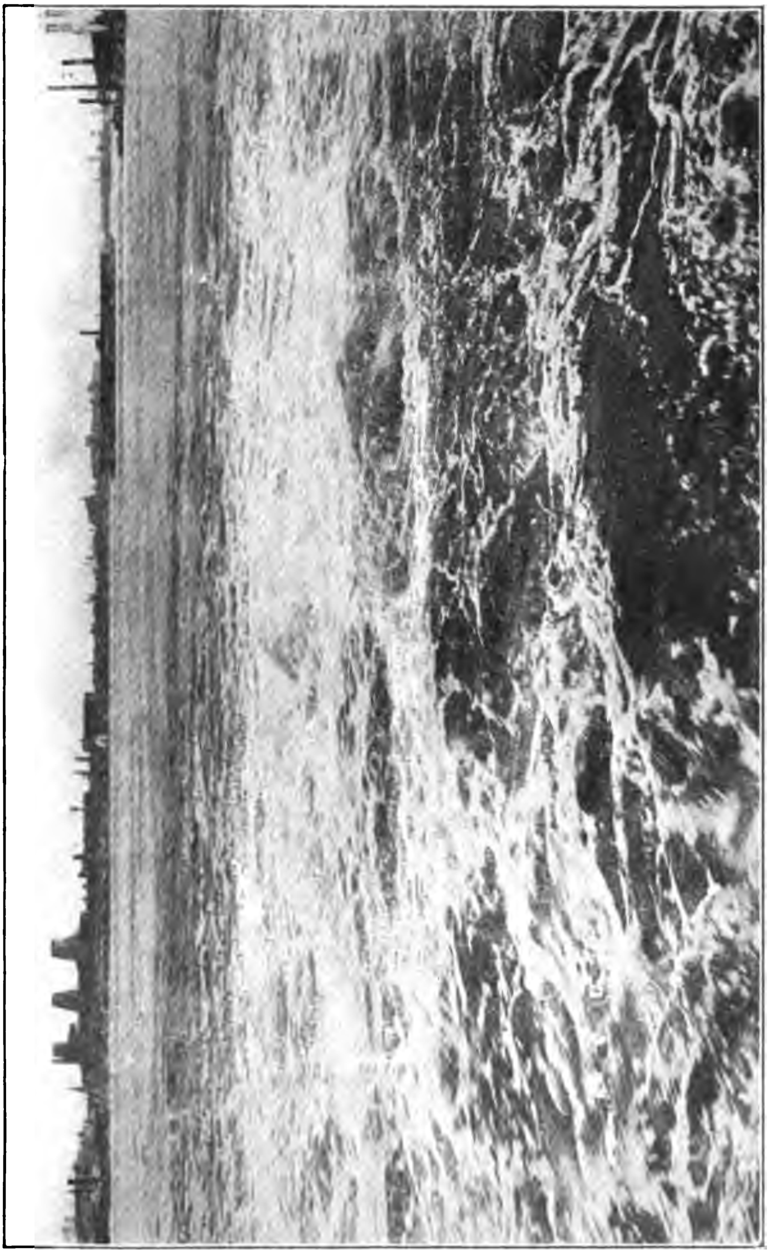
(*B*) BLOWS AND BLANKETS

133. Cause of Blows.—A blow occurs, or is apt to occur, when the air pressure in the tunnel is greater than the pressure of whatever cover, earth or earth and water, there may be lying over the roof of the tunnel. The denser the ground the less is the danger of a blow. Blows may occur quite unexpectedly, owing to some local and unknown diminution of the cover or to a change in the nature of the cover, or to some open vein or pocket, for example, an unfilled bore hole or the hole caused by the withdrawal of a pile, leading from the tunnel to the surface or the bed of the waterway.

134. Effect of a Blow.—When a blow starts, the compressed air rushes out with violence through the opening. Men have been swept off their feet, carried through the funnel shaped opening in the ground and shot up through the funnel into the water above. One man to whom this happened has survived the experience. The air pressure in the tunnel falls, the air becomes befogged, the water, no longer held back by the air, begins to pour into the tunnel. A man begins to think that the light of day is a mighty good thing, but a long way off. On the surface a spouting geyser tells the story (see Fig. 128).

135. Fighting a Blow in the Tunnel.—It is now that the tunnel man has a chance to show his mettle. He must fight a blow from the first sign until it is sure that he cannot beat it. Held by his fellows from being swept away he will stand by the blow, cramming sacks, coats, shirts, mud, hay, sawdust or any other thing into the hole, hoping that it may become choked and the blow stopped. If forced finally to retreat by the rising flood all that can be done is for the men to get back along the runway to the emergency lock and to lock themselves out, leaving the shield and the tunnel back to the air bulkhead wall nearest the face for the time being to their fate (see Fig. 129).

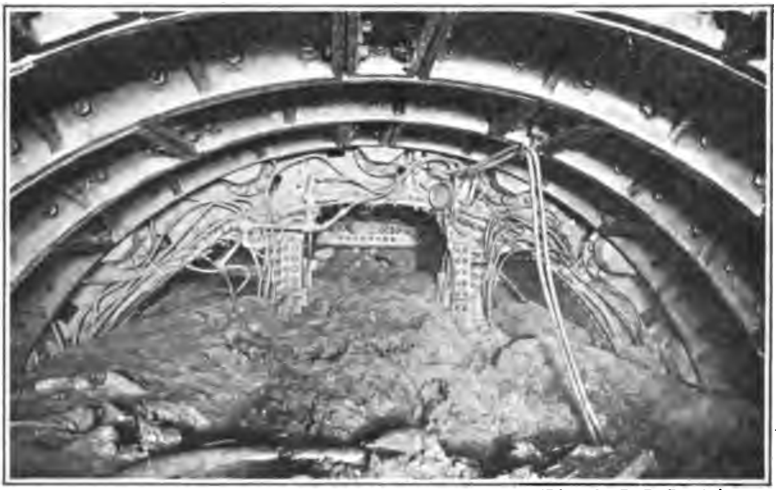
136. Fighting a Blow on the Surface.—The next move is on



(*Photo by P. P. Pullis.*)

FIG. 128.—A "blow." The East River, New York, during the construction of a tunnel for the dual subway system of New York. (Courtesy of *New York Transit Commission.*)

the surface. Barge loads of clay will be dumped over the blow until the opening is closed and the air pressure in the tunnel can be restored. Then the men can get back through the lock, clean up and go ahead. Sometimes it is not possible to dump the clay, en masse, from a scow, as where the blow occurs under a pier or alongside a dock. In such cases the clay may be bagged and the bags thrown over the blow. It may take twenty or thirty thousand bags to shut off one blow.



(Photo by P. P. Pullis.)

FIG. 129.—The result of a blow in a tunnel. (Courtesy of *New York Transit Commission.*)

137. Example, Hudson River.—On the south tunnel of the two tunnels of the Hudson and Manhattan Railroad between Morton Street, New York, and Fifteenth Street, Hoboken, N. J. (A-17), a serious inrush of silt occurred through an open door in the shield which was then alongside the coal dock of the Lackawanna Railroad. The shield was being shoved with the top door open. Suddenly, without warning, a column of silt shot through the opening into the tunnel, burying one man and forcing the rest to flee. The whole tunnel from shield to bulkhead became filled solidly with mud.

138. Method of Recovery.—Two heavy yacht main sails were used to make a double canvas sheet, 60 ft. by 40 ft. This sheet was spread on a flat barge. Weights of pig iron were attached to the corners of the sheet and the sheet was then placed and fixed

in such a manner that 30 ft. overlapped the position of the shield and the tunnel and 30 ft. were beyond the face. The barge was then withdrawn and the sheet allowed to drop to the river bed. Thousands of clay-filled bags were thrown in over the canvas. One of the air pipes in the bulkhead in the tunnel separating the flooded portion from the rest of the tunnel was opened. The imprisoned silt shot out to a distance of 40 ft. and for eight days on end this mud flowed in and was loaded on the tunnel cars. As the tunnel was emptied a cavity was formed in the river bed in front of the shield. At last the canvas was drawn through the open door and blocked the opening. More clay was thrown into the river to hold the canvas in place. The lock door was opened and the face regained.

139. Blankets.—As usual, prevention is better than cure. Wherever possible place a good blanket of clay over the route of a tunnel where the cover is thin or where blows may be expected. This clay blanket is deposited from barges before the shield comes along.

140. Clay for Blankets.—The clay must be suitable for the purpose. It must pack densely and must not be washed away by the current of the water and it must stand up well against the air when it is trying to escape.

141. Thickness of Blanket.—The thickness of the blanket should be as great as possible. When the work is being done under navigable waterways the permissible depth of the blanket may be regulated by public authorities. In open ground the engineer should strive for at least a 10-ft. blanket and more if he can get it. Even if he must dredge the blanket up after it has done its work this is cheaper than fighting blows.

142. Examples of Blankets.—On the Blackwall tunnel (E-7) the blanket had a maximum thickness of 10 ft., was 450 ft. long and 150 ft. wide. Twenty-five thousand cubic yards of clay were used. On the East River work for the Pennsylvania Railroad (A-19) the blanket had an average thickness of 12 ft., was 3,000 ft. in length and took nearly 285,000 cu. yd. of clay. In addition to this nearly 90,000 cu. yd. of clay were dumped into the river at blows. The total cost of this blanket was $304,000. It is difficult to see how either of these tunnels could have been built by the shield method without the blanket.

143. Permanent Blankets.—In certain cases a permanent blanket has been laid. An example is afforded by the crossing

of the East River at New York on the line of Sixtieth Street, Manhattan, (A-35) by the 18-ft. tunnel for the rapid transit system of New York. The river was 115 ft. deep at the deepest point along the line of the tunnel. A heavy layer of clay was laid down over the line of the tunnels as part of the permanent construction. The clay was covered with rip rap stone deposited from scows. The gradient of the tunnel was such that at the deepest point of the channel it emerged wholly from the river bed and was driven through the blanket, which remains in place over the completed tunnels.

144. The Value of Clay.—Clay is one of the tunnel man's best friends. He may sleep well with a good thick blanket of it over his work.

(*C*) DRIVING SHIELDS

145. The Shove.—The work covered in the operation of forcing the shield ahead under the action of its propelling jacks acting against the completed lining is called "shoving" the shield. This operation is important, as the position of the shield determines closely the position of the lining built within it. The shield must be guided carefully, therefore, during the shove. The shield is shoved by admitting to some or all of the propelling jacks the hydraulic pressure which is used for the purpose. The jacks have a stroke equal to, or slightly greater than, the width of one ring of the lining. While the shove is being made the shield moves forward so that the tail portion is drawn forward over the last completed rings, but when the shove is over the last ring erected is still overlapped by the tail.

146. Guiding the Shield.—During the forward movement the shield is guided solely by the jacks, except in mud, where assistance in guiding is given by varying the volume of mud admitted. By using the jacks on one side without using those on the other the shield may be moved from one side toward the other. Similarly, by using the jacks at the top the shield may be pointed down and by using those at the bottom it may be pointed up. It is necessary for the man in charge of the shield to know what he is to do about shoving and it is customary for the engineer, after the position of the shield has been checked by the survey corps, to issue information as to the position of the shield, often accompanied by instructions as to the jacks to be used, the volume of mud to be admitted and so on. It is the foreman's

duty to use the combination of jacks that will point the shield in the desired direction. It is an important duty, as a careless and incompetent man may cause a serious deviation from alignment and grade in the course of one shift.

147. Getting Iron Bound.—The shield has a certain clearance over the iron, that is, the inside diameter of the tail of the shield is somewhat greater than the outside of the lining. This clearance usually will not exist as an equal clearance all around when the tunnel is being built. The lining will rest against the tail at some point so that the clearance will be zero there while at the opposite point it will be a maximum. It will be seen that the clearance determines the degree to which the shield may get out of line with the lining. In order to reduce the escape of air and to afford as good as possible a form for the erection of the lining the clearance is made as small as feasible. At the same time it is often required that the shield shall point, not parallel with the lining but at an angle thereto. In tunnel parlance it must have a "lead." If the shield lead gets beyond a certain point the skin of the shield will begin to bear heavily on the lining. This will lead to all kinds of trouble. The shape of the tail of the shield may be distorted and that also of the lining. If the shield gets "iron bound" (as the saying is in cast iron lined tunnels) at the top it may make it difficult and even impossible to get in the key segments. It is, consequently, important to watch the clearance between the lining and the tail. This should be done by the survey corps every time it checks the shield, and the information given to the foreman. It will be the foreman's duty to watch this himself also and to guard against getting iron bound by making sure that he does not get any excessive leads on the shield. Sometimes it is most difficult to avoid this as when a shield is persistently "diving" so that strong upward leads are necessary.

148. Bending of Jacks.—While the matter of the size of the jacks belongs rather to the design than to the operation of the shield it should be remembered that the thrust developed by the shove does not come axially along the jacks. The jack heads are offset in order that the force of the thrust may be taken by the skin rather than by the flanges of the iron lining, Even if this is not the case, as where wooden cants or pre-cast concrete blocks are used for lining, the shield seldom will be shoved square with the lining. This means that a bending action is developed

in the jack plungers. If the plunger is bent by this action delay is occasioned as the defective jacks will have to be taken out and replaced. Careful watch should be maintained on the jacks so that any signs of bending may be detected instantly. The remedy lies in designing them of ample size to take the greatest bending action that may occur.

149. Packing Jack Cylinders.—It is an advantage to be able to tighten the packings without removing the jacks. The different types of jacks are discussed in Chap. IX, and need not be repeated here, except perhaps to say once more that simplicity is essential.

150. Pushing Back the Jacks.—When the shield is being shoved blind, all the shield jacks cannot be withdrawn at once, because the pressure of the earth will force the shield back again. In ground where shoving blind can be done only those jacks necessary to permit the placing of a segment of the new ring can be drawn back at a time. When the segment is in position the jacks are pressed against this and the jacks opposite the next plate withdrawn. This is repeated until all the segments are erected.

151. The Face Jacks.—The function of the face jacks is to support the face where such support is needed. These jacks have a forward movement so that when fully extended they reach in front of the hood if the shield has one. If the shield has no hood, the face jacks can reach rather more than the width of one ring of the lining, ahead of the cutting edge. The stroke of the jacks is a little more than one ring width. The diameter of the face jacks is less than that of the shoving jacks and the pressure of the latter can overcome that of the face jacks. The total capacity of the face jacks should be equal to the maximum head of ground and water combined. When the face is being excavated and timbered down, the timbering is supported by bringing out the face jacks to their full stroke and holding them against the timbering. When the excavation for one ring width has been done the propelling jacks force the face jacks to close, either with their full pressure on or with their exhaust valves partly open.

152. The Erector.—As previously described the erector has a rotary motion combined with an in-and-out motion. When a segment of the lining has to be picked up and erected the erector is rotated until it points at the segment which is lying on the floor or on the car which has brought it into the tunnel. The arm of the erector is then moved out until it reaches the segment. The

segment is attached to the erector by the grip on the end of the arm and the erector is then rotated with the segment attached until the arm is pointing at the place which the segment is to occupy. The arm is then extended so that the segment is in place against the tail of the shield and is held thus until the segment has been bolted to the segment of the same ring previously erected and to the segments of the adjacent ring. The various types of rotating mechanisms, grips, etc. have been described in Chap. IX.

153. Other Use of Erector.—The erector is used in an auxiliary degree to keep the shape of the lining true by thrusting against the last erected ring, while the bolting up is going on, after the key has been inserted. For example, if the lining has a tendency to flatten the erector will be thrust out against the lining at the top and thus help to diminish the distortion tendency until the bolting has been completed.

154. Two Erectors.—In some large shields two erectors have been used with quite satisfactory results. It is an open question, however, whether two erectors lead to much greater speed than one, at least in tunnels up to 27 ft. in outside diameter. On the Blackwall tunnel with two erectors a ring of iron is stated to have been erected in a minimum time of 35 minutes. (*Proc. Inst. C. E.*, vol. 130, page 81.) On the Hudson River tunnels of the Pennsylvania Railroad with one erector a ring was commonly erected in 30 minutes. The comparison between the two may be seen as follows:

TABLE XXVI.—TIME TAKEN TO ERECT ONE RING, BLACKWALL TUNNEL, RIVER THAMES, ENGLAND, AND PENNSYLVANIA RAILROAD TUNNELS, HUDSON RIVER, N. Y.

Ref. No.	Tunnel	Outside diam., feet	No. of erectors	No. of segments per ring	Weight of one ring, pounds	Minimum time to erect one ring, minutes	Minimum time per segment per erector minutes	Pounds erected per minute
(E-7)	Blackwall	27	2	15	31,360	35	4.3	896
(A-18)	Pennsylvania	23	1	12	30,319	30	2.5	1,010

It seems, therefore, that one erector can keep pace with two in tunnels up to this size. As the one erector is mounted on the axis of the shield it is in a better position to place the key segment. It is possible to imagine that in a tunnel of larger size, 40 ft. diameter perhaps, two erectors would be better than one.

155. Shoving the Shield.—Let us suppose that the shield is ready to shove. The foreman has the engineer's written instructions telling him that he is so much off line and grade and that he is to get such and such a lead on his shield, and if in silt he is to take in so many cars of silt, and that he is to use a straight ring or a taper ring of lining as the case may be. He arranges the combination of shield jacks that his experience and judgment teach him will be likely to give him these leads and—if in mud—the door opening that will admit the required volume. A man is stationed at each side of the tunnel and another at the top, each with a graduated rod marked so boldly that the foreman, standing on the tunnel floor, can see all the graduations. These rods are held against the shield so that, as the shield advances, its distance from the leading end of the last completed ring can be seen by the foreman and by the man in charge of the jack control. If the desired leads are not attained early in the shove the combination of shield jacks in action is changed. It is useless to shove a shield "all square" and then put on the lead at the end of the shove by giving the shield a final kick with a few jacks. The lead must be put on at the start of the shove and held to the end, as the object of the lead is to move the shield over while traveling and not merely to have it pointing in a certain way. In soft ground it may not take longer than a few minutes to make a shove, so the foreman must be wide awake and prompt to act.

(*D*) ERECTING LINING

156. Small Tunnels.—In tunnels up to 13 or 14 ft. in diameter all the work of erection is done by hand. The segments are brought up to the face on small cars. The men slip iron rods or wrench handles through the bolt holes in the segments and lift them from the cars. Four men can lift one segment, which is usually made to weigh not more than 350 lb. The lower segments are dropped into the bottom of the shield tail and bolted up to the last completed ring and to one another. When the ring has been erected to the point where the horizontal joint of the ring being built is above the level of the working floor, fresh planks are laid down to extend the floor across the new ring, and the side segments are lifted by hand and put in place. The upper segments are reached by throwing a few planks across the tunnel to form a platform a little below the horizontal

axis of the tunnel. The segments next to the key are lifted to the platform and propped up from the platform or from the bottom of the tunnel until the key is put in. The props are then removed, the bolts slipped into the holes of the circumferential joint and all the bolts tightened up. The whole operation will be done in half an hour or less per ring.

157. Cast Iron Lining in Large Tunnels.—The general routine is the same in large tunnels. The erection starts at the bottom and proceeds upward. The bottom segment goes in first, then the next segment on one side and then the next on the other. This alternation goes on until the key is reached. The only difference is that the work of lifting the segments and putting them into place is done by the mechanical erector instead of by man-power. The men merely have to give the segments their final adjustment and to put the bolts through the bolt holes.

158. Erection Procedure.—Owing to the heavy weight of the segments they are not lifted off the cars by hand, but a chain is attached to the segment and the erector arm and the segment is dragged off the car and dropped to the bottom. The segment is then attached to the erector for erection and swung into position. The last segment to be erected prior to the key is set with its lower flange on the upper flange of the adjacent segment below and rotated around the inner edge of the two adjacent flanges until in position in order to permit it getting past the end of the segment at the other side of the key. The key segment is attached to the erector arm and pushed radially into position. This last operation is simple if the lining is true in shape. If, on the other hand, the last ring previously erected is out of shape, if the shield is iron bound at the top or the lining carelessly erected, the difficulties connected with placing the key are great and much time is wasted in this performance. It is essential, therefore, for good work that the lining must be designed so that it will not deform excessively under the loads that may come upon it, that it is erected true to shape and that the alignment of the tunnel is closely followed.

159. Trailing Platform.—When a trailing platform is used it is not necessary to build platforms at each shove in order to reach the upper part of the tunnel. The solidly built trailing platform gives the men a greater sense of security than the loose planks laid across the tunnel and their movements can be made with greater decision. Owing to the additional facilities for erection

and the greater number of men that can be occupied it takes hardly any longer time to erect a ring of lining in a large tunnel than in a small one.

160. Erection of Wood Lining.—The care which must be taken in the erection of cast iron lining applies equally so to wood. The cross section must not be allowed to become distorted.

Each segment in a ring must bear evenly and fully on its radial joint against its next door neighbor in that ring. Keeping the ring in proper shape will help to achieve this. The radial joints in successive rings should break joint, as this helps greatly in keeping shape. If any distortion tendency shows, hold the lining from going out of shape by turnbuckles or by posts or by both together. The stresses are often greatest during the first few days, while the earth is undergoing the disturbance due to the passage of the shield. Furthermore the pressure of the shield jacks may increase the tendency. It is possible, therefore, in many cases to remove these supports after a certain period. If this is not possible then the lining is not strong enough and either some secondary lining of concrete, brickwork, or metal must be placed within the primary wooden lining or a change must be made in the design of the wooden lining itself, (*e.g.*, by making the cants of deeper section). In most cases permanent posts or ties cannot be permitted within the bore, as the use of the tunnel would be made impossible thereby.

Equal care must be taken in seeing that the leading face of the wooden lining forms always a plane and that the surface of this plane is normal to the desired course of the tunnel at that point. With a more or less compressible material like wood there will be a constant tendency for the shield jacks to cause unequal compression of the ring against which they abut and this, in turn, will lead to many kinds of trouble in keeping proper line and gradient, to say nothing of the watertightness of the tunnel in open wet ground.

161. Erection of Concrete Block Lining.—The care and precautions necessary for cast iron and wood linings apply with equal force to linings made of pre-cast concrete block. It is impossible to speak in wholly definite and specific terms about the details of the erection of concrete blocks, since the design of the individual block may be quite different in one case from that in another. Some blocks are plain voussoirs of un-reinforced concrete, others have projecting lugs and corresponding recesses

cast in them which cause the adjacent blocks and adjacent rings to be interlocked, some are plain and some are reinforced. The troubles and difficulties in a large tunnel will be different from those in a small, and those in firm ground different from those in soft. The general principles will remain the same. The rings are built up from the bottom, segment upon segment and ring after ring. Distortion of shape must be prevented either by making the segments deep enough in themselves or by applying temporary support. Each block must be of exact size and shape. The radial joints must bear over their surface. Dirt must not be allowed to get between the segments or between the rings. The front surface of each ring must be a plane normal to the tunnel's course. A close watch must be kept for cracked or broken blocks. The whole thing, as with all types of lining is incessant care and watchfulness to see that all possible trouble is prevented from happening rather than to patch up trouble after it has happened.

162. Cleaning Off.—It is necessary for good work to clean all dirt and debris from the bottom of the tail of the shield before starting to build up a new ring. All dirt must be removed also from the front flange of the last complete ring against which the new ring is to be erected. It is obvious that proper joint cannot be made if there is any foreign substance within it. The lining cannot do its full work unless the joints bear properly on one another. The presence of dirt in the joints is a fruitful source of broken plates owing to the pressure of the shield thrust becoming concentrated at one point by reason of the dirt.

163. Bolting Up.—The matter of bolting up an iron lined tunnel is apt to be overlooked or slurred to the detriment of the tunnel. Unless all the bolts are tightened when the iron is erected and kept tight thereafter it is impossible to keep the lining in its proper shape. When a ring of lining is erected, the bolts in the radial joints must be tightened thoroughly and a good proportion of those in the circumferential joint also. It is a good plan to make sure that all the bolts in the circumferential as well as in the cross joints are thoroughly tightened below the working floor as these will not be accessible again until the tunnel is finished and the working platform removed. Above the working floor all the cross joint bolts must be tight and at least those in the circumferential joint adjacent to the cross joints. The other circumferential bolts can be left to be gone over by the bolting

gang after the erection is completed. As the shield is forced ahead, the pressure of the jacks against the lining will cause the circumferential joints to be squeezed together. While the pressure is on the shield jacks is the best time to get the bolts tightened in these joints. As thorough as possible a job should be made of the bolts. A good watertight tunnel cannot be made if the bolts are neglected. Furthermore, a good job cannot be had by neglecting the bolts during the shield driving period with the idea that this can be done later on. It is true that the nuts can be screwed tight but this will not draw the joints close together. It is obvious that, when the tunnel is finished, open joints cannot be tightened by screwing up the bolts.

164. Size of Wrench.—The size of the wrench depends on the size of the bolt. For bolts of 1½ in. diameter and over a wrench with a 2-ft. handle is enough for the first tightening. For the tightening up gang, pieces of pipe which can be slipped over the handle to increase the length to 3 or 4 ft. should be provided.

165. Trouble to Get Bolts Tightened.—Most of the men in the tunnel hate and despise bolt tightening and think that the engineer who insists on tight bolts is making much ado about nothing. If this matter were made a feature of the specifications more often than it seems to be, the field engineer and the inspector would be saved much worry and better work would be had with less trouble.

(*E*) GROUTING

166. Purpose of Grouting.—The Grouting Plant was described in Chap. X, par. **82** to **88**. The purpose for which grout is ejected outside the lining of a tunnel is to fill the voids in the ground so that there is a close packing all around the periphery of the tunnel supporting the lining by distributing the earth pressure uniformly over its surface. Furthermore, the grout will form, to some degree at least, and generally to a high degree, a water proof envelope outside the tunnel lining.

167. Result of Grouting with Hand Syringe.—As stated in Chap. X, the grouting machine was invented by Greathead in the year 1886 primarily for use in London clay. When he was building the Tower Subway (E-2) in 1869, lime and water had been mixed in a tub and forced through holes in the

cast iron lining plates by means of a hand syringe. This was done to fill the annular space outside the lining, left by the passage of the tunnel shield. The result was not good, partly because the hand syringe required the mixture to be made too fluid for proper setting and partly because the pressure which could be applied to the syringe was not enough to force the grout home into every interstice.

168. Results Obtained with Pressure Grouting.—The results obtained with the grouting machine described in Chap. X, are very different. The force is applied by the compressed air turned into the machine and thus may be as great as desired. In usual work, pressures of 30 to 60 lb. per square inch are found to be enough. Cases have occurred, in normal air, where pressures of 500 and even 1,000 lb. per square inch have been used. The main purpose of grouting in these shield driven tunnels is to fill the annular space left by the shield around the outside of the lining. Each segment of the lining has a tapped and plugged hole in its skin through which the grout can be forced. The process, in general, consists in beginning at the lowest, or at least at one of the lower, holes. The grout is ejected through this hole until it reaches the hole above. When this happens the grout pipe is inserted in the upper hole and so on until the highest hole is reached, when the full pressure is brought on the grout. The process is not confined to tunnels lined with cast iron; linings of concrete block, timber cants, mass concrete, brickwork or stone masonry are equally amenable to this treatment.

169. Process of Grouting.—Figure 130 shows the operation of "grouting up" behind the iron lining of a tunnel. The man at the left in the foreground is manipulating the grout discharge pipe. It is found more convenient not to screw the nozzle of the grout pipe directly into the tapped grout hole but to interpose a nipple and valve between the lining plate and the grout pipe so that, when the section is filled with grout, the valve can be closed until the grout has set, instead of trying to remove the grout pipe and to put in the plug while the grout is still liquid. The nipple and valve can be seen clearly in the view. The next two men are charging the grout pan with water and cement respectively and the man on the right is the inspector, recording the "batches" of grout ejected.

The art of grouting has developed into an almost special craft

FIG. 130.—"Grouting up" an iron-lined tunnel. The Greathead type of grout pan is being used. Pennsylvania Railroad Hudson River Tunnels (A-18). (Courtesy of *Pennsylvania Railroad*).

and a man well skilled in the craft is a most valuable asset on any piece of tunnel work. The more difficult the work, the more valuable the craftsman.

170. Experienced Operators Essential.—Not only is the process used to fill the voids behind the tunnel so that the lining gets its abutment from the earth, but to stop leaks at the face, to repair damaged masonry, and to waterproof shafts. It is of almost universal application in under water work. Grout, ejected in this way will travel 500 ft. from the point of ejection if the conditions are favorable. Great experience is necessary to get the best results possible under any given set of conditions. The pressure to be used, the consistency of the grout, the amount of sand to be mixed with the cement, the place at which the ejection shall be made, are all questions which arise and which can be solved properly only by the application of long experience to the particular combination of circumstances presented.

A great deal depends on the man who actually does the grouting. An experienced foreman with an instinct for this work will achieve results in sealing off heavy flows of water which appear almost incredible. The best results will come from a combination of skilled engineering planning and supervision coupled with experienced men to carry out the work.

171. General Hints on Grouting.—It is impossible to give any rules for grouting which will suit all conditions; some few general pointers, however, may be attempted.

1. For sealing off water leaks behind tunnel linings a 1 to 1 cement and sand mixture is the most usual, although neat cement has been used largely also. About 6 or 8 gal. of water per bag of cement (with a 1 to 1 mix) is found to be a fair average allowance. Use as little water as possible.

2. The sand must be carefully and finely screened. On the Catskill Water Supply tunnels an enormous amount of grouting was done, as described and discussed in *Trans. Am. Soc. C. E.*, vol. 83, pp. 980 to 1,079. The sand was screened so that 100 per cent would pass a sieve having 64 openings per square inch, and 45 per cent pass a sieve having 1,600 openings per square inch, the wires of the sieves being, respectfully, 0.035 in. and 0.013 in. in diameter. The sand must be free from loam. If there are any lumps in the dement (which happens sometimes when cement is kept in the tunnel for a while), the cement also must be screened.

3. The air pressure used must be as low as possible and yet able to force the grout into the place required. The tendency is to use too high a pressure. It is important also not to let a blast of air from the grout machine follow the batch.

4. It is often advisable to go over the grouting more than once to displace water left by the first operation. Usually a second grouting will do but sometimes three or four are necessary. It often happens that a stage is reached where the leakage is not shut off entirely but a small modicum of inflow remains and that this modicum is driven from one point to another by further groutings. This is an indication that the process has been carried as far as practicable; for the time being immediate further grouting will do no good. This seepage will tend to diminish by itself, as a rule. Further careful grouting after the lapse of a few years may result in a complete sealing of the seepage.

5. In cases where the water seams are large, good results are obtained by mixing bran or fine chopped cotton waste with the grout. (See *Trans. Am. Soc. C. E.*, vol. 80, p. 636.)

6. Vent pipes at the summit for the discharge of entrapped air are necessary. This is often overlooked.

7. The hose, valves and all apparatus should be of the best quality and kept perfectly cleaned and washed and blown out thoroughly at the end of every shift or oftener if necessary. A blow off valve should be provided at the end of the hose so that a blocked pipe can be cleared.

8. Grout holes should be cleaned with a rod, or by having air, or water blown into them before beginning to grout. The hose should not be allowed to kink and everything should be made as easy as possible for the grout to travel freely to the place where it is supposed to go.

172. Conclusion.—The secret of success in grouting is careful, skilful and patient work based on an intelligent scheme of operation. The volume of cement required may be enormous and the effect may not be felt until the grouting has been carried to the point of refusal. On the four new tunnel crossings of the East River for the New York subway system (Ref. Nos. A-27, A-28, A-30 and A-35) 136,000 bbl. of cement were used.

173. Gravel Packing.—During the last few years another method of filling the annular space around the lining of a shield

driven tunnel has been developed. The method is in principle similar to grouting, but the material used is the fine screenings from the stone crusher. This sharp grit is forced under air pressure outside of the lining where it packs tightly, filling the annular space. This method has the construction advantage over grouting that the material is immediately solid and requires no time to set.

(*F*). CALKING AND GRUMMETING, CAST IRON LINING

174. Necessity of Waterproofing.—The work of making waterproof the iron lining of a tunnel driven through waterbearing ground reduces the permanent cost of pumping and makes the tunnel better suited for its use. In soft mud the ever present seepage of a leaky tunnel has the effect of causing slow but constant settlement of the tunnel. This has a bad effect on the alignment as well as on the structure itself.

175. Sources of Leakage.—In an iron lined tunnel of the usual type there are only three possible sources of leakage, namely:

(*A*) The grout holes.
(*B*) The bolt holes.
(*C*) The joints between the segments.

176. Grout Holes.—This source of leakage may be considered as of minor importance. The usual specifications for the grout holes read as follows:

"Each tunnel segment shall be tapped with a hole near the center for a grouting connection. The hole shall be threaded with a standard bolt thread and closed by a screw plug."

In some cases a pipe tap is specified. Beyond making sure that all grout holes have their plug in position and perhaps smearing red lead on the thread, nothing needs to be done with the grout holes.

177. Specifications for Waterproofing Bolt Holes.—The specifications for waterproofing the bolt holes may read as follows:

"Leakage around the bolts shall be prevented by applying under the washers at the head and nut of each bolt a grummet of hemp well worked up with a paste of red lead, or a mixture of red lead and white lead, in boiled linseed oil. If leakage is found after the grummeting the bolts around which leakage occurs shall be removed and the grummeting renewed until leakage is stopped."

178. Grummets.—These grummets are rings of twisted hemp yarn known as "lath yarn" and are just large enough to slip

over the bolt. They have a cross-section of about ½ in. The grummets are soaked in a thick mixture of red lead and oil and are then hung up to drip off before being used. One of these under the washer at each end of the bolt is usually enough to stop leakage, but where the head is particularly high, or where the bolt is obliquely in the bolt hole it may be necessary to use more than one.

179. Grummeting.—The grummeting and calking (to be described later) are best performed as an entirely distinct operation and it should not be the practice to put the grummets on at the initial erection of the iron. After the grummets are on, the nuts on the bolts must be tightened thoroughly. With bolts of 1¾-in. diameter it will take two men using a bolting wrench having a handle 3 ft. long. Bolts are not thought "tight" unless they will resist without turning the weight of an ordinary man (150 to 160 lb.) on a wrench 2 ft. 6 in. long.

180. Lead Grummets.—In certain cases lead grummets have been used and have given good results. They are made either by cutting lead pipe, of a suitable diameter, into short lengths or casting them in moulds, the latter method being the more satisfactory. Lead grummets were used on the Greenwich Subway (E-11) and on the Rotherhithe tunnel (E-17) in London and in these cases the outer ends of the bolt holes were beveled off. When the bolts were tightened up the lead grummets were squeezed into this bevel, filling the hole completely. The statistics of the leakage of these and other tunnels will be given later.

181. Calking of Joints.—The joints between the segments are waterproofed by "calking." As described in Chap. VIII, each segment is made with a recess cast along the inner edge of the flanges where these abut against the adjacent flange when erected in the tunnel. These recesses form the "calking grooves." After the iron has been erected waterproofing material is placed in these grooves.

182. Unmachined Joints.—On the Concorde Metropolitain tunnel (F-12) across the Seine in Paris, where the cost of machining the flanges was considered to be prohibitively high ($14.00 per ton) a layer of creosoted soft wood of a minimum thickness of $\frac{3}{16}$ in. was used between the segments on both circumferential and cross joints. The wood acted, in this case, as the primary waterproofing medium and the calking grooves were merely pointed with cement. Seurot remarks (*Proc. Inst. C. E.*,

vol. 188, page 389) that the delay, extra labor and annoyance due to the wooden packings was greater than the cost of machining the segments, even at the high price demanded.

183. Standard Calking Grooves.—To all intents and purposes it may be considered standard practice in subaqueous work to machine the abutting surfaces of the segments and to do the waterproofing by calking the grooves.

184. Calking Materials.—Three chief materials have been used for waterproofing purposes, namely:

(*A*) Rust calking.
(*B*) Lead.
(*C*) Combination of rust and lead.

185. Rust Calking.—In rust calking a mixture is made of sal ammoniac and iron borings or filings; sulphur may be added as this accelerates the rusting process. The mixture is made up in pails so that it is always fresh. It is calked into the grooves with tools to be described later and after it has been in place for some time the whole mass turns into a dense cement-like substance with the appearance of rusted iron.

186. Mixture.—In the Blackwall tunnel (E-7) the mixture was 1 lb. of sal ammoniac to 400 lb. of iron filings. On the Hudson River tunnels of the Pennsylvania Railroad (A-18) two mixtures were used. In the sides and invert 2 lb. of sal ammoniac and 1 lb. of sulphur to 250 lb. of iron filings or borings and in the arch 4 lb. of sal ammoniac and 3 lb. of sulphur to 125 lb. of iron were used.

187. Calking Tools.—The tools used are shown in Fig. 131. They consist of a "pusher" with which the mixture is put in place and a flat headed tool, rather less in width than the width of the groove, for driving the mixture firmly into place. Hand or pneumatic hammers are used for this purpose. Hand hammers seem to do better work.

188. Width of Calking Groove.—As the calking groove is merely cast in the segments before the machining is done it follows that the groove varies in width, consequently calking tools of several different thicknesses have to be supplied.

189. Machined Grooves.—Seeing how important the calking operation is and how rigid the inspection needed to obtain good results it seems at least an open question whether, for large and important work, it would not be an actual economy to machine the calking recesses.

190. Calking Pockets.—In some cases, where the tunnel has passed through ground unusually wet, the calking groove has been carried around the bolt holes in the form of pockets so that the calking could be driven all around the shanks of the bolts. This has been found to give satisfactory results, but it makes the process of calking distinctly more difficult. In order to make the calking thoroughly good at the bottom of the pockets each bolt has to be removed while this portion of the pocket is being calked and has to be replaced before filling the upper portion. The work is expensive and it is doubtful whether just as good results cannot be obtained without pockets, relying on grummeting.

Fig. 131.—Tools used in calking with sal ammoniac and iron filings the joints of an iron-lined tunnel. (Courtesy of *Pennsylvania Railroad.*)
1. 2-lb. hammer. 2. Narrow calking tool. 3. Medium calking tool. 4. Wide calking tool. 5. Cutting and cleaning tool. 6. Pusher for placing the mixture in the groove.

191. Cleaning the Groove.—Whatever the form of the grooves, they are thoroughly scraped out with a special tool, cleaned with cotton waste and washed with a stream of water under a pressure of at least 50 lb. per square inch.

192. Illustrations of Process.—Figures 132 and 133 show the process of calking in a tunnel. In Fig. 132 the men are working in the roof. The three front men are driving the calking mixture into the grooves. The man behind is tightening up the bolts after having put on the grummets. The end view of the tunnel ring behind the last man shows the form of the pocket calking groove. In Fig. 133, the men are at work on the side of the tun-

Fig. 132.—Calking and grummeting in the roof of an iron-lined tunnel. Pennsylvania Railroad Hudson River Tunnels, New York (A-18). (Courtesy of *Pennsylvania Railroad*.)

Fig. 133.—Calking and grummeting the side of an iron-lined tunnel. Pennsylvania Railroad Hudson River Tunnels, New York (A-18). (Courtesy of *Pennsylvania Railroad*).

nel. The two men at the left are tightening up a bolt which has just been grummeted. The next two men are driving the calking mixture and the two on the right are placing the mixture into the joint prior to calking it tight. The pail in which the grummets are absorbing red lead is to be seen. Near the feet of the third man from the left some grummets are hung up to drip.

193. Operation Unpleasant.—The rust calking and grummeting operation is a most unpleasant one for those who are doing and inspecting it. The grummets and the men grummeting are a sticky mess of red lead and the smell of ammonia from the calking mixture is almost overpowering. It is a most monotonous job and yet it cannot be slighted. Every bolt and every inch of joint has to be treated with the same meticulous care. It is usually necessary to do the work in an air pressure that will ensure the water being driven from the joints as percolating water will prevent the rust jointing from being tight. After a length of tunnel has been calked and grummeted the air pressure is removed and every bolt and every joint inspected. All leaks are marked, the pressure restored, the faulty places gone over again and the process repeated until the tunnel is passed as "dry."

194. Records of Waterproofing.—It is advisable and almost essential to record the progress of the waterproofing on a diagrammatic development of the tunnel ring, so that the inspection force can mark on the diagram the first calking and all the subsequent revisions until the tunnel is finally passed.

195. Sequence of Calking.—It is found convenient to calk all grooves and grummet all bolts in the roof first, then do the sides and finally the invert, rather than to do a complete ring at a time. At any rate this is so in tunnels of such a size that a man cannot reach all parts from one position. The calking and the grummeting are usually done at the same time and by the same gang.

196. Calking Pockets and Grummets Compared.—It has been found that with pocket grooves it takes 1.15 man-hours to calk 1 lin. ft. of joint, and grummet the corresponding number of bolts, while with pocketless iron it takes 0.415 man-hour to do the same work.

197. Lead Calking.—In some tunnels, notably in the tunnels under the East River for the rapid transit system of New York City, lead has been used to calk into the tunnel joints. The specifications for this work contain the following:

"Joints shall be made watertight by a continuous calking of metallic lead in the calking recesses. The lead must be as nearly as practicable of the same width and thickness as the width of the recess. Before the segments are erected, the rebates to form the calking recess shall be scraped clean and free from the tar coating. Before calking, the recesses must be thoroughly cleaned by means of an air jet or water jet under high pressure and if required by scraping. If leakage is found after calking the joint shall be re-calked, the lead being removed and renewed if required."

198. Example, Pennsylvania Railroad, East River Tunnels.—On the East River tunnels of the Pennsylvania Railroad (A-19) the iron lining was at first calked with rust calking. Some difficulty arose in connection with the calking, caused by the water seeping through the lower part of the lining where the air pressure was not high enough to balance the water head. Lead wire, calked cold into the grooves was tried and proved so successful that the rust calking was abandoned. Pneumatic hammers were used and excellent results attained.

199. Example New York Rapid Transit Tunnels.—The lead calked tunnels of the New York rapid transit system, built in 1914–1916 are, to all intents and purposes, bone-dry throughout and there seems no doubt that lead is a first class material to use.

200. Difficulties With Cast Iron Lining.—In *Trans. Am. Soc. C. E.*, vol. 69, pp. 395-396, Japp says: "Owing to the difficulties of making rust joints, it looked as though the flanges of the iron were slightly bent in bolting up, and the slackening of a bolt was sufficient to cause the iron to spring away from the hardened rust calking and permit a leak . . . the difficulties of the broken plates and watertightness would be avoided to a large extent if mild steel tunnel lining could be used instead of cast iron."

201. Combination of Rust and Lead.—In the Greenwich subway (1898) (E-11) and in the Rotherhithe tunnel (1904) (E-17) a thin strip of lead or lead wire was calked into the bottom of the calking grooves and then the remainder of the groove was calked with rust calking. In both cases excellent results as regards watertightness are reported.

202. General Observations.—From a study of what has been done up to the present time we believe that, unless it is certain that harmful corrosion is likely to occur from having lead and iron in close contact, lead is the best material so far developed for waterproofing cast iron lining. This applies to the grummet-

ing of the bolts as well as to the calking of the joints. Anything more discouraging than hemp grummets dripping with red lead cannot be imagined, unless it is the stench of the sal ammoniac, sulphur and iron borings. The metallic lead on the other hand, is clean and can be placed in normal air pressure. If lead grummets are used they should be mold cast to fit exactly round the bolts and to fill amply the space, into which they are to pack. For extreme cases of obliquity of the bolts specially thick grummets could be cast or a hemp grummet used in combination.

203. Depth of Calking Groove.—The following table shows the depth of calking groove used on certain existing under-water tunnels.

TABLE XXVII.—DEPTH OF CALKING GROOVE IN THE IRON LININGS OF CERTAIN EXISTING TUNNELS

Ref. No.	Tunnel	Date	Outside diameter, feet	Depth of calking groove, inches	Pocket or plain
(A-5)	Sarnia	1888	21.00	2	plain
(E-7)	Blackwall	1891	27.00	2	plain
(E-13)	Lea	1901	12.16	1¼	plain
(E-8)	Waterloo and City	1893	12.87	¾	plain
(E-11)	Greenwich	1898	12.75	1⅛	plain
(E-15)	Baker St. & Waterloo	1900	12.81	⅞	pocket
(A-18)	Pennsylvania Hudson River	1904	23.00	1½	mostly plain
(E-17)	Rotherhithe	1904	30.00	2	plain
(A-27)	Old Slip, Rapid transit, N. Y.	1915	18.00	1¼	plain

There seems a tendency to increase the depth of the groove as the diameter of the tunnel increases. While there is nothing essentially bad about this in so far as the circumferential flanges are concerned there does not seem any reason for it. The difficulty of making a tunnel watertight is a function of the greatest head of water under which the tunnel lies and not of the tunnel diameter. If a small tunnel can be made watertight with a groove ¾ in. deep, a large tunnel under the same conditions of head, soil, etc., can be made tight equally well. A shallow groove is preferable, particularly in the cross flanges because of the stress conditions of the lining.

TABLE XXVIII.—REPORTED SEEPAGE

Ref. No.	Tunnel	Approximate date finished	Maximum depth high water to invert feet	Leakage per sq. ft. of outer surface per 24 hours, U. S. gal.	Nature of calking in cross joints	Nature of calking in circumferential joints	Kind of grummets
(A-5)	Sarnia	1890	78	0.0540	wood	lead	
(E-7)	Blackwall	1891	80	0.0035	rust	rust	yarn
(E-11)	Greenwich	1899	70	0.0060	lead, rust	lead, rust	lead
(A-16)	Battery	1908	90	0.0250	lead	lead	
(E-17)	Rotherhithe	1908	75	0.0008	lead, rust	lead, rust	lead
(A-17)	Hudson & Manhattan Railroad	1910	95	0.0440	rust	rust	yarn
(A-19)	P. R. R. East River	1910	90	0.0050	lead	lead	yarn
(A-18)	P. R. R. Hudson River	1910	100	0.0008	rust	rust	yarn
(A-34)	Dorchester	1919	75	0.003	note	note	note

NOTE.—All these tunnels are cast iron lined except the Dorchester tunnel which is lined with wood, waterproofed inside with felt and tar and covered with concrete lining inside this.

204. Leakage.—Table XXVIII shows the volume of leakage stated to be measured in certain tunnels. The figures are given as reported, but in these statements there is an element of doubt inherent to the nature of the case. It is not stated in all cases exactly the portion over which the leakage is measured. The water measured may include surface water draining into the tunnel from the approaches. Water may be used for cleaning the tunnels and this may be measured. The figures are given to show what has been attained and as a guide for judging the capacity of the permanent pumping plant which should be installed. The age of a tunnel has sometimes an influence on the leakage. Frequently the leakage decreases the longer the tunnel has been built.

205. Probable Leakage.—From this table it may be considered that in a cast iron lined tunnel, calked and grummeted, the probable leakage, expressed in U. S. gallons per square foot of outer surface may be as follows:

Maximum....................0.040 gals. per square foot per 24 hours.
Average.....................0.004 gals. per square foot per 24 hours.
Minimum....................0.001 gals. per square foot per 24 hours.

Table XXIX based on the above is given to show the volume of seepage that may be expected in tunnels of various diameters for the maximum, average and minimum ratios taken.

TABLE XXIX.—PROBABLE SEEPAGE

Outside diameter of tunnel feet	Outside area per 1,000 lin. ft., sq. ft.	Volume of seepage water in U. S. gal. per 1,000 ft. of tunnel per 24 hours		
		Maximum, gal.	Average, gal.	Minimum, gal.
5	15,700	630	65	20
10	31,400	1,260	125	30
15	47,100	1,880	190	50
20	62,800	2,520	250	70
25	78,500	3,140	320	80
30	94,200	3,770	380	90
35	109,900	4,400	440	110

It should be considered possible to attain the results shown in the minimum column by proper care and attention to the erection of the iron in the first instance, so that no foreign substance is between the flanges and the rings true to shape, followed

by thorough workmanship and close inspection of the process of calking and grummeting.

(G) ENGINEER'S SUPERVISION

206. The Engineer's work of Supervision.—The engineer's work of looking after the tunnel building consists of two main parts as follows:

(*A*) Supervision: This means seeing that the work is carried out in accordance with the letter and spirit of the contract and the specifications.

(*B*) Recording: This means leaving as perfect as possible a written and graphical record of what was done and why it was done. It also involves making an analyzed record of cost of the different processes of construction.

The engineer in charge of a tunnel work will not be able, by himself, to do all the work of supervision and recording. He must have a corps of assistants and inspectors who will act as his deputies. The following paragraphs are intended as a suggested outline of what the duties of such a field corps should be and what the work of supervision and recording involves.

207. Working Force.—A detailed account of the force on each shift should be kept on prepared forms. The men outside of the air locks should be kept separate from those within. The following should be recorded:

(*A*) The section of the work on which the man is working.

(*B*) The proper title or "rating" of each man.

(*C*) The rate of his pay.

(*D*) The particular job he is doing.

(*E*) The length of shift worked.

208. Shield Record in Tunnel.—A record box should be kept in each tunnel alongside the heading telephone. The card for the inspector's notes should be kept in this box, and all measurements entered on it as soon as made. The instructions for driving the shield are entered on this card and the results of the last shield check (see Chap. XVI). Whenever the telephone is moved ahead the box should be moved also so that the inspector can call up the office if the driving instructions are not, or cannot be, followed.

209. Temperature.—A thermometer is kept in each record box and a reading taken and recorded on each shift. This record should be placed in a graphic record form also.

210. Sample of Air.—It is well to have a daily analysis of the air in the heading taken for the CO_2 gas content at the same hour each day. It should be taken close to the shield about 3 ft. above the floor and away from the current of air from the supply pipe. Special pumps can be bought for this purpose. They draw a sample of the air into a metal tube, which can be detached from the pump and sent to the office for analysis. The results of the analyses should be recorded on a graphic chart. Further reference on this matter is made in Chap. XVII.

211. Air Pressure.—The air pressure in each tunnel should be recorded for each shift. If there is more than one set of locks in operation the pressure at each lock should be recorded. The gauge gives the pressure above that of the atmosphere. The inmost pressure is the sum of the gauge readings at each successive lock. This should be checked by reading on the gauge in the office, which is directly connected with the working chamber by a special pipe. A graphical record of the air pressure should be kept.

212. Air Compressors.—The readings of the air compressor revolution counters should be taken regularly several times a day. All counters should be read whether every compressor is running or not. The volume of free air per unit of time delivered to the tunnel should be computed from these readings and a graphical record of the volume of air per man per unit of time should be kept.

213. Emergency Air Lock.—When going through the air locks note should be taken that the doors of the emergency locks are open toward the shield so that the men may escape in case of need.

214. Air Supply Pipe in Heading.—The air supply pipe should be kept up as close to the shield as possible. It is important that the flap valve be in place at the end of the pipe.

215. The Shield, Supervision.—The assistant engineers and the inspectors should make themselves thoroughly familiar with the shield and should watch its erection, learn how it is put together and know the names and functions of all parts. All break-downs, defects, distortions, leaks or other matters whether or not causing delay to the work should be noted. Each pocket of the shield should be numbered so that, in reports and records, no doubt can exist as to which is meant.

216. The Shield, Records.—All labor on repairs or alterations to the shield should be noted and an account kept of the materials,

spare parts, etc. used in making them. The labor and materials should be recorded in a special shield record book.

217. Shoving the Shield, Supervision, Bolts.—The shield must not be shoved until the bolts in the last ring have been tightened. It is especially important that all the bolts in the radial joints are tight, all those below the working floor and at least those in the circumferential joint above the floor which are next to each cross joint. The bolts in the rings already erected tend to loosen after each shove and for this reason there should be a gang of men doing nothing else but tightening bolts behind the shield.

218. Turn Buckles and Posts.—If turn buckles or posts are being used to retain the shape of the lining, they must be tight before shoving.

219. Leads.—The shield must be shoved with the lead ordered. The lead must be obtained on the first 6 in. of the shove and kept to the end. The engineer or inspector should take a position in the tunnel or on the shield from which he can see the three rods measuring the lead. The difference between the readings of the two side rods give the side lead. The vertical lead cannot be measured directly except when a full face is being excavated and breasted ahead down to the bottom. The vertical lead will be computed generally from the top and two side readings. The mean of the side readings gives the distance that the horizontal axis of the shield is ahead of the last ring and the difference between this mean and the top reading gives half the vertical lead. If the proper leads are not obtained at once the foreman must be told and the reason discovered. It may be carelessness or defective jacks. In either case the shove should be stopped and appropriate remedies applied. There is no other way to keep good line and gradient.

220. Muck Taken In.—In mud if all the shield doors are closed and no muck taken in the shield will tend to rise. The strength of the tendency is greater the larger the tunnel. In such cases even with a top lead opposed to it the shield will rise as it follows the flowing mud ahead of it along the line of least resistance, namely upward. In such ground, therefore, the orders for shoving are a combination of leads and of quantities of mud to be taken in and the inspectors must see that the number of cars of muck ordered are actually taken out and that the cars are filled, as a slight divergence from the quantity ordered has a nullifying effect on the engineer's aims. The method of guiding the shield

by the regulation of the volume of ground admitted cannot be used in its entirety, as other considerations such as the rise and distortion of the lining behind the shield and, when there is an adjacent tunnel ahead, the tendency of the following shield to raise and push over and distort the leading tunnel has to be considered. The less muck taken in by the following shield the more marked are the effects on the leading tunnel.

221. Shoving the Shield, Records, Open Doors.—When shoving into mud the following should be recorded (*a*) the number and position of doors open, (*b*) the number and position of doors partly open, (*c*) if openings are obstructed by timber, the nature of the obstruction.

222. Shoving the Shield, Nature of Face.—If the ground is being excavated ahead of the shield, a sketch of the face should be made showing the position of the different formations or strata, piles, boulders or anything worth noting, with dimensions where possible. It is convenient to have a rubber stamp showing the outline of the cross-section of the shield.

223. Leads.—At the end of the shove the two side and the top leads should be taken and recorded. The average number of jacks in use at any one time and the hydraulic pressure should be recorded. It is convenient to number each jack so that no doubt can exist as to which is meant. The time of starting and ending each shove should be recorded from the time the pressure is turned on to when it is turned off.

224. Mucking.—The number of cars of muck sent out for each ring must be counted and checked with the lock-tender's tally. The degree of fullness of each car should be noted and an estimate of the yardage made. If, in mud, the silt appears unusually dry or hard or soft or sandy a note should be made, as the behavior of the shield in pockets of special quality is often puzzling.

225. Clearance.—The clearance should be measured at the horizontal and vertical diameters and recorded at the end of each shove.

226. Diameters.—The horizontal diameter should be taken at the front end of the ring after the shield has been shoved against it. It is measured by holding the zero of the tape at one side of the tunnel and swinging the other end until the longest reading is secured. The vertical diameter is taken in a similar way. As with nearly all these matters of record, it is most convenient to keep a

graphic chart of these measurements. This gives an instant mental picture of the situation.

227. Erection of Lining, Supervision.—Make sure that all muck and dirt is removed from the tail of the shield before putting the first segment in the bottom. This muck should not be thrown back into the tunnel invert but cast up on the working floor. It is always found, even where the greatest care is used, that the overhang of the iron constantly decreases owing to dirt getting into the bottom joints. The more careless the work the worse is this disease. When the bottom segment is in place the jacks opposite to it are released to hold it in position and the bolts put in and tightened. All the cross joints are to be made good as the erection proceeds and thoroughly well tightened before the circumferential bolts are tightened. It is easiest to keep good shape this way. If the preceding ring is narrow in the horizontal or vertical diameter, then, after the ring has been erected and all the cross joints are thoroughly tight the erector arm should be pushed against the ring to force the lining out and thereby get the diameters correct. Then the arm should be released and the circumferential bolts tightened. Before the working floor is put down the bolts in the preceding ring must be gone over.

228. Erection of Lining, Records.—A record should be kept of each ring, whether it is a straight or tapered ring; if it is a taper, what kind. Each ring should be numbered and the number marked on it. If there are several different patterns or types or weights of rings, the particular kind must be noted. The time taken to erect each ring should be noted. This is taken from the time the first plate is being lifted off the car to be slung into the bottom up to the time the key is in place and the bolts passed as tight. The horizontal and vertical diameters and the clearance should be recorded before the erection of the new ring is begun. Breakdowns of the erector or erector pressure pipes should be noted and the reason and extent given.

229. Office Work.—Each assistant engineer and inspector should keep a diary and fill it in at the end of each shift. The record should show the date, the shift, the number of men of each class at work. The time taken to erect each ring, the diameters, leads and other measurements taken are also noted.

230. Ring Record.—A detailed record of each ring is kept in the office on printed sheets made for the purpose. These embody all

the information taken on each ring, the leads obtained, number of cars of muck, position of tunnel as checked by the survey corps, etc.

231. Force Distribution Sheets.—The men working on each shift should be recorded on special sheets ruled for the purpose. The men in compressed air should be kept separate from those in normal air.

232. Compressor Records.—The compressor records are kept to show the volume delivered to the tunnel and the volume furnished per man.

233. Shift Records.—The shift records show the rings erected, the time taken, diameters and results of shield checks. Their chief use is for the information of the succeeding shift.

234. Daily Report to Chief Office.—A daily report to the chief office should be made out each morning. It is convenient to have it made out up to say, 8 o'clock a.m. This is because the working day is considered usually to start at that hour. The report gives the progress made during the previous 24 hours, the force employed, the air pressure, the temperature, the nature of the ground, any important accidents or incidents and other items of importance or interest to the chief engineer. The reports are conveniently made out on ruled and printed cards so that the matter is handled as one of routine and not as a special compilation for each day. If several tunnels are under construction at one time it is useful to have a special color of card for each tunnel.

235. Monthly Report.—A monthly report to the chief engineer is also advisable. This embodies the generalized progress made, ground encountered, air pressure and similar physical information. It should contain the quantities of work put into the construction during the month and to date and the percentage of work done to date. It may be well to include cost data also on this form and possibly the resultant unit costs of the work as developed to date. Full cost data can hardly be presented in such progress reports as it is not until the work is completed that the full information is at hand. It is useful, however, to make this a part of the monthly report as it forces the record of the costs to be kept constantly more or less in shape and up to date. This work has a strong tendency to lag behind and thus lose half its value.

236. Weekly Inspection.—The tunnel should be inspected thoroughly from end to end once each week. The purpose of

this is to discover any evidence of distortion or weakening in the lining, excessive leakage and such matters. In a tunnel large enough for an overhead runway it is necessary to traverse the tunnel three times to make this inspection, once along the runway, and once along each side. The inspection should be rigid and thorough. Any broken segment, missing bolt, missing grout plug or other defect must be noted and reported at once. This inspection should not be made each week by the same man. Whether anything to report or not is found a report covering the inspection should be made.

237. Engineer's Organization.—The Engineer's organization should be carefully worked out. Each department such as designing, field supervision, and accounting should be placed under one responsible head and this head should be held to account for the results of his department. At the same time, these men must not be allowed to look upon themselves as the heads of a lot of independent departments resentful and impatient of anything which comes from any other department. The best results only come from a healthy spirit of team work. Each head of department will have a number of men below him and these men must be so organized that there is a constant staging of authority and responsibility from the most junior position to the head. There should be no doubt whatever in any man's mind as to whom he reports and all confusion and overlapping of duties must be eliminated. It is most useful to draw up a diagram of the organization and to work to this rather than to build up a haphazard and unorganized lot of men equipped with titles which are confusing and duties which are ill-defined. Needless to say, the utmost care should be taken to fill each position with the man best fitted for it by training, experience and temperament, not forgetting that for some positions, and these not the least important, technical training may rank lower than character. Every man should have the utmost support from his superior all up the line, unless there is something palpably wrong and in such case a private talk is to be commended above a public call-down. Each man of the same grade and of the same length of service should receive the same pay. In no case should a man of superior title receive pay less than a man holding an inferior title.

237. Relations with Contractor.—No pains should be spared to establish good relations with the contractor's forces. This

does not mean hob-nobbing with them but, an attitude of complete fairness which shows that the provisions of the contract must be performed with all reasonable diligence and exactitude and that the contractor and his forces will be treated without harshness and spite on the one hand or feeble good nature on the other. It is a great help if the leading members of the engineer's force have at least as much experience as those of the contractors, and this holds all along the line. It is very hard for an inexperienced inspector to deal with an experienced foreman.

CHAPTER XIV

MAINTENANCE AND INSPECTION

A. INSPECTION AND REPAIRS

1. Maintenance Work.—When a tunnel is finished and ready for operation the work of the engineer is not over, but is changed to that of maintenance. This work consists of periodical inspection of the structure and its appurtenances, and of making such repairs and minor alterations as the inspection shows to be necessary or desirable. In the following the maintenance of the structure proper is considered principally.

2. Regular Inspection.—A tunnel structure is usually of such massive and seemingly permanent character that regular inspection may seem unnecessary. Nevertheless, natural forces are constantly at work to weaken it, and the very fact that it is not exposed to view makes it important to inspect it purposely to detect signs of weakness. This inspection should be made a matter of regular routine, the period between each inspection being determined by the character and the condition of the structure. The routine of the inspection varies with the character of the lining.

3. Unlined Rock Tunnel.—In solid rock a tunnel is sometimes left unlined to save the initial cost of the lining. In such a case the weathering of the rock must be watched. Rock originally sound may become unsound on exposure. The unsoundness may take the form of local or general softening of the rock structure or of loosening masses of rock. Furthermore, some rock, often the soundest and hardest kind, is subject to intense internal stress. Masses of rock may become detached and fly off with great force, even long after the excavation has been made. The percolation of water through seams and crevices also may cause the detachment of masses of rock, particularly as such water often is charged with acids or alkalis having a strong affinity for the rock, thereby causing gradual or rapid decay.

4. Method of Inspection.—All exposed rock, therefore, should be narrowly scanned at regular intervals. It should be sounded

with a hammer, which gives a characteristic "ring" when the rock is sound. It is prudent to have a regular scaling gang doing this work. The surface must be gone over thoroughly with hammers and bars and any loose and rotten rock knocked down. The engineer should not take the work of this gang for granted, but should satisfy himself at frequent intervals that a condition of absolute safety exists. The best cure for scaling rock is to line the tunnel.

5. Wood Lining.—When a tunnel is lined with wood there may be, in addition to the carrying members proper, wood packing outside of the regular lining, where overbreak has occurred. The carrying members should be inspected for attacks of fungoid disease. An examination should be made to see whether the timbers bear properly against each other, whether any movement has taken place and whether the longitudinal bracing is in position and adequate. The packing should be examined for decay and to see whether it properly fills the voids. Sometimes the packing has not been put in as solidly as should be at the time of construction. Weakness of any kind disclosed by the inspection should be repaired immediately by replacing or supporting the faulty timbers. The fire hazard of a wood lined tunnel should be considered; fire fighting apparatus should be provided and kept in working order.

6. Cast Iron Lining.—The inspection of a cast iron lined tunnel should cover the cast iron segments for breakage and corrosion, the bolts and grout plugs for looseness and corrosion, and the structure in general for leakage.

7. Broken Plates.—A broken plate should be repaired, but it is difficult to take it out and replace it, and it is often a dangerous operation to attempt to do so. Usually it is better to reinforce it. This may be done in various ways. The plate may be filled to the depth of its flanges with concrete, reinforced perhaps, with steel rods. Turnbuckles may be used to bind the broken segment together as shown in Fig. 134. As shown in the figure it has been possible in this case to place the turnbuckle without removing the connecting bolts of the lining. This is often an important advantage.

8. Broken Plate Sign of Weakness.—A broken plate is a sign of weakness. Either the tunnel at that place has been out of shape from the start; or the segments at the time of erection

have been drifted violently into position causing excessive tensile stress in the metal; or there has been some localized intensity of earth pressures. A thorough sounding of the iron lining in the vicinity of the broken plate should be made; some grout plugs should be taken out to examine for voids outside of the lining. Should such be found, or should there be any reason to suspect unsymmetrical pressures on the lining, a cautious, skilful and thorough grouting is indicated. This will equalize the earth thrusts and bring a uniformly distributed abutment against the lining.

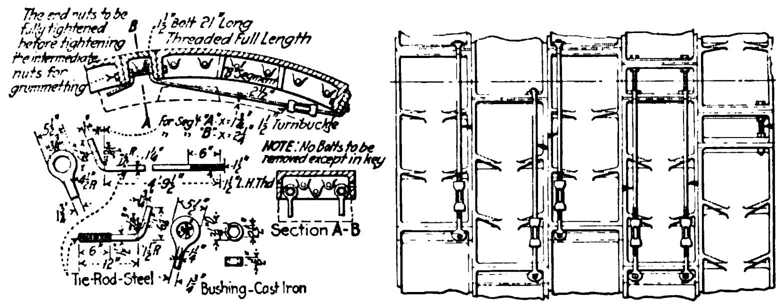


FIG. 134.—Method of reinforcing broken cast iron lining segments by means of turn-buckles. With this design the bolts need not be removed in order to place the turn-buckles.

9. Decay of Cast Iron Lining.—As a rule, cast iron tunnel lining is not readily subject to corrosion, although it may be affected locally by water heavily charged with sewage, acids, or trade wastes, which may enter between the uncoated joints of the segments. The matter of so-called graphitization of cast iron is also worthy to be considered. Sometimes pieces of iron buried in water or earth, including recently laid cast iron water pipe, have been found completely graphitized; the iron has disappeared, leaving carbon in the form of the original casting, but without any substance or strength. Although we know of no case in which cast iron tunnel lining has been so affected, it may not always be immune from it. Perhaps some compositions of cast iron are more subject to it than others, and if so, the selection of the composition of the iron used for a tunnel lining should be made accordingly. Examination should be made periodically for decay of the lining and if it occurs, the weakened portion should be reinforced.

10. Bolts and Grout Plugs.—Inspection should be made of all bolts and grout plugs. If any are missing they should be replaced; if loose they should be tightened and if corroded they should be renewed.

11. Leakage.—The structure should be examined for leaks. Any leaking joints should be re-caulked and leaking boltholes should have the bolts tightened or the grummets replaced. The matter of leakage is considered further in par. **18–21.**

12. Concrete Lining.—A concrete tunnel lining should be examined for cracks, decay and leakage. Cracks should be repaired by cutting out the concrete, along the course of the break, to a depth of several inches, and refilling the cut with mortar. Serious cracks indicate local weakness, and it often is advisable, where they occur, to drill holes through the concrete and grout behind the lining.

13. Decay of Concrete.—Concrete sometimes decays, perhaps due to the cement used, but more frequently perhaps, in a tunnel lining, due to seepage water, charged with impurities. Decay may be discovered by going over the surface with a hand chisel. If the concrete rings hard and looks sound, it is probably in good order, but it may be further tested by drilling into the concrete with hand or air drills. A scale may be set up, whereby a penetration of so much per a given number of blows represents hard, sound concrete, one with more penetration second quality concrete, and one over a certain penetration an unsound concrete. Further evidence may be obtained by taking a core boring from the concrete on which compression and other tests may be made.

14. Cure of Decay.—It is easier to find decay of concrete than to suggest a remedy. The cause must first be found, but even if it is known it is not always possible to take effective steps to prevent future trouble. For example, the decay may be found to be due to acid water in the ground around the tunnel, but it is seldom possible to go outside the tunnel and cover it with a coating impervious to acid. It might be suggested that an alkaline substance be forced outside the lining with a grout pump, but it is open to doubt whether such a process would be so completely and perfectly done as to afford the protection desired.

15. Secondary Lining. The most certain method of strengthening a decayed concrete lining is to build a secondary lining inside the concrete lining. Usually, however, there is not much room

to spare inside the tunnel, so that this secondary lining must be made of cast iron, steel castings or structural steel, which will not occupy as much space as a masonry construction. It may be necessary even to cut away the interior surface of the concrete to the depth of the flanges of the new metal lining in order to maintain the clearance required within the tunnel. The metal lining should be secured to the concrete with bolts anchored into holes drilled in the concrete. When erected complete, some judicious grouting between the metal and the concrete should be done to make a close contact. This grouting must be done under light pressure, unless the metal lining can be securely braced inside, otherwise the lining will be forced away from the concrete and become distorted. The metal lining should be calked and grummeted as any other metal lining and concrete may be filled between the flanges.

16. Access to Structures.—In order to perform the inspection and maintenance work described in the preceding paragraphs, access must be had to the tunnel. In tunnels used for any kind of vehicular traffic the inspection usually can be carried out while the tunnel is under operation. The necessary repair work may be carried out during periods of the day or night when no traffic passes through the tunnel. Where the traffic is continuous throughout the 24 hr. this must be operated on a single track during the hours of least traffic, past the place where the work is in progress. In tunnels carrying water, gas or other liquids the flow usually can be cut off for enough time to permit inspection. If large repairs have to be made it may be necessary to provide a temporary by-pass. In water intake or discharge tunnels for power houses, the matter of access is often difficult because the flow of water may have to be continuous and because no means are provided to shut off the flow through the tunnel. It is advisable that such tunnels be provided in duplicate and it must not be forgotten to furnish a gate at the seaward end so that the flow may be stopped. If the tunnel can be laid dry, it is generally possible to by-pass the water in a temporary flume.

17. Decay of Discharge Water Tunnels.—Experience has shown that the warm, oily discharge water has the effect of destroying mortar, concrete and even cast iron. The best remedy in such a case, if the destruction has not gone too far, is to place a tight wooden lining inside of the original lining. The

quality of the original work is most important for such tunnels. It should be of the best.

18. Leakage.—Leakage into a tunnel should be constantly observed and records kept of the observations, because the leakage is largely an index of the soundness of the structure. In most cases leakage decreases with the age of the structure. If, therefore, after a time the leakage suddenly increases, this will indicate a weakness somewhere in the tunnel. The observations should cover the volume of leakage, the position of the leaks and the composition of the leakage water.

19. Volume of Leakage.—The flow may be measured by a self registering device attached to the pumps emptying the sumps, or by a periodical count made of the strokes of the pump, or by observing the time the flow requires to fill a measured vessel. The volume of the flow may be represented conveniently by plotting, the abscissæ being the time and the ordinates the volume. For definite information care should be taken that the leakage water from the tunnel is measured alone and not mixed with leakage water from the shaft or with water otherwise introduced into the tunnel.

20. Position of Leaks.—It should be observed whether the leakage water originates from definite leaks or from more general damp spots. Definite leaks should be stopped. Damp spots may dry out in time, or the whole surface, where they occur should be waterproofed. In relatively dry tunnels a large proportion of the apparent leakage water may be due to condensation of the moisture of the outside air entering the cooler tunnel.

21. Composition of Leakage Water.—Water leaking into a tunnel frequently has chemical composition which differs greatly from place to place. It is advisable to have the composition analyzed to determine whether or not the water may have a harmful effect on the structure.

22. Cleanliness.—Tunnels should be kept clean. No dirt or rubbish should be permitted to collect. The drains should always be clean and the pumps in perfect working order.

B. OBSERVATIONS OF MOVEMENTS OF TUNNELS IN SILT

23. Purpose of Observations.—It has been observed that tunnels driven through silt are in constant motion. The actual movements are small and present experience indicates that they have no effect on the safety of the tunnel structure. Neverthe-

less, the very fact that the tunnels move according to laws not yet fully comprehended, makes it imperative for the engineer responsible for the maintenance of a tunnel through silt to have complete and full records of the movements of the tunnel.

24. Observation of Movements.—The movements affect the the line, the elevation and the shape of the tunnel, and all these items, therefore, should be covered by the observations, which should be made at regular intervals. The length of the intervals depends on the extent of the movements. Immediately after the construction of the tunnel the intervals should be short, perhaps one week or one month. Later, when the trend of the movements has been established, the length of the intervals may be increased to perhaps six months or a year. The observations should be made by the same methods and at the same points each time, so as to obtain a consistent series of comparative observations and preferably by the same observers.

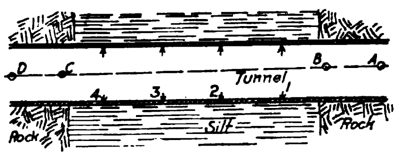


FIG. 135.—Diagram plan of a tunnel with its ends in rock and its mid portion in soft mud.

25. Measurement of Lateral Movements.—Let us imagine a tunnel as shown diagrammatically in plan in Fig. 135. The ends of this tunnel are in solid rock, while the mid portion is in mud and has been in a state of movement during the construction. If a line $A\ B\ C\ D$ is laid out within the tunnel and monumented at A, B, C and D in the rock, then at any future time this line can be reestablished. If plugs are established on the side of the tunnel as at 1, 2, 3 and 4, then the offset measurements from the line $ABCD$ to the points 1, 2, 3 and 4 will show any lateral movements. To eliminate the effect of possible change of shape of the lining, points should be established on both sides of the tunnel at the station points 1, 2, 3 and 4. The intervals between the stations should be regular. The plugs must be attached solidly to the lining, must not be subject to decay or corrosion and must be convenient for taking the measurements.

26. Measurement of Vertical Movements.—The vertical

movements are measured either by ordinary leveling or by direct observation from fixed points established within the tunnel.

27. Observation by Leveling.—When ordinary leveling methods are used the leveling is started from fixed bench marks within the portion of the tunnel which is built in rock. Levels are taken at regular intervals on previously prepared points throughout the tunnel. It is requisite to have records of the tide at the time the levels are taken, because the levels are affected by the tide. Tide gauges, therefore, must be provided and read. Self recording tide gauges are best for this purpose and preferably should be placed in the tunnel. For this purpose a hole is drilled through

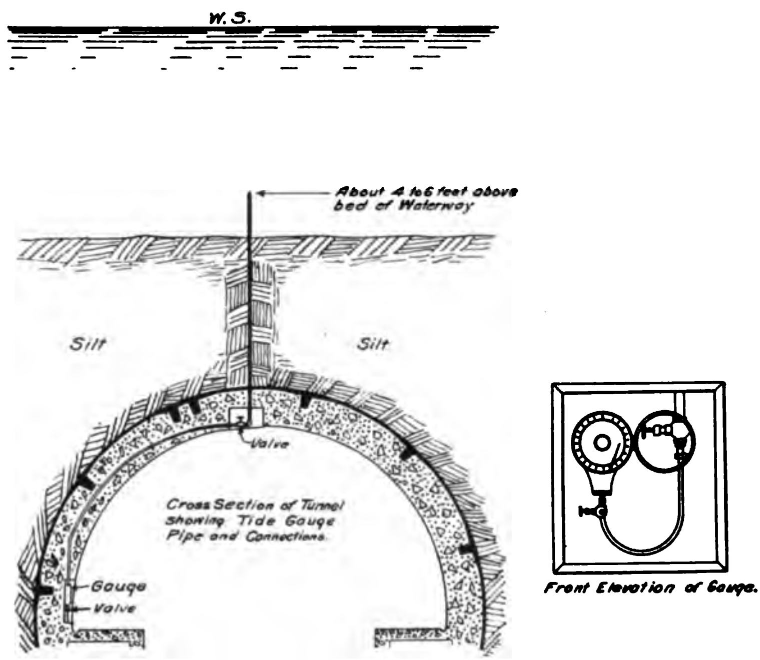


FIG. 136.—Recording gauge for showing the tidal variation of the elevation of the surface of the water above a tunnel in mud.

the lining through which a pipe is inserted vertically and reaching to above the river bed. If the tunnel is lined with cast iron the hole through the skin of the lining is tapped and a threaded bushing placed within the hole so as to form a watertight sleeve or stuffing box for the pipe. If now a recording pressure gauge

is connected with the end of the pipe which is inside the tunnel, the changes of the elevation of the water will be recorded. By calibration the changes can be referred to the datum elevation used in the tunnel survey. Figure 136 shows the arrangement. The gauge must be located so that the use of the tunnel is not obstructed.

28. Observations from Fixed Points.—Fixed points may be established in the tunnel if rock is found at some reasonable distance below the tunnel. A hole is formed in the tunnel lining

Fig. 137.—A recording gauge in the invert of a tunnel. This gauge records the movement of the tunnel in relation to a fixed vertical rod passing through the bottom of the tunnel, and having its lower end wedged in the bed rock below. (Courtesy of *Pennsylvania Railroad*.)

and a casing pipe is jetted or forced down through the silt and is landed firmly with its lower end resting on the rock. A diamond or shot drill is then used to drill into the solid rock. The drilling is done from the tunnel, the drill rods protected by the previously driven casing. The hole being drilled a rod of non-corrosive metal is prepared. This rod is split at its lower end and a wedge is inserted, butt down and sharp end up. The rod and

the wedge are of such size that when lowered through the casing, inserted into the hole drilled in the rock and driven home therein, the wedge will expand the rod, so that it is held firmly in the hole. Grout may be poured down into the hole in the rock to help hold it firmly in place.

Stuffing boxes are provided to permit movements without letting mud or water into the tunnel. A recording instrument is placed in the tunnel for recording the movements of the tunnel in relation to the end of the rod. The instrument should be arranged so as to multiply the actual movements. Figure 137 shows a photograph of such an apparatus.

29. Measurements of Shape.—Before the tunnel is placed in operation it is possible to make the tunnel record its own changes of shape by fixing a rod, preferably of Invar metal, to one side or the top or bottom of the lining so that a pencil carried by it may scribe a record on a clock-driven sheet of paper fixed at the opposite end of the tunnel diameter. With the tunnel in use such methods are not possible, and the lengths of the diameters must be measured with rods or steel tapes.

30. All Observations Taken at the Same Stations.—All the different observations should be taken at the same stations. The points necessary for taking the measurements should be well defined, preferably plugs of noncorrosive metal, set firmly into the tunnel lining. The distance between the observation stations should be uniform, usually 50, 100 or 200 ft. The observations should be a sequence of the observations made during the construction so as not to form a gap in the records. This is important, as it enables one to tell the actual effect on the tunnel of subsequent structures, such as another tunnel or docks or piers resting on piles.

31. Temperature Observations.—Temperature observations are important only in special cases, but they are easy to take and are always at least of theoretical interest. The observations may cover the air in the tunnel, the tunnel structure and the surrounding ground. Simple non-recording bulb thermometers may be used or recording electrical resistance thermometers. The latter have the advantage of giving a continuous record and not needing so much attention. Their record can be made to be written in the office. The thermometers will be placed at intervals in the tunnel. If intended to read the temperature of the structure or the ground, they are placed in holes drilled for the

purpose. Electric resistance thermometers are best for this purpose, because they can be buried permanently, the only connection needed to pass into the tunnel being a few insulated wires.

32. Character of Movements.—In order to facilitate the interpretation of the observations made of the movements of the tunnel, a short statement will be given of the movements observed in previous tunnels built through silt and the probable causes of these movements.

33. Causes of Movements.—It has been stated before that the movements of the tunnel are with the silt rather than in the silt; that the silt is supersaturated with water and increases and decreases its volume according to the thickness of the film of water separating the solid particles, and that the thickness of the film decreases with increased superimposed load, while it increases with a decreased superimposed load. Hence the vertical movements are caused by the fluctuations in the depth of silt below the tunnel and the changes in shape by the fluctuations in the depth of silt within the vertical height of the tunnel. The cause of the horizontal movements is more obscure, but these movements are of minor importance.

34. Character of Vertical Movements.—There are four phases of vertical movements, namely:

(*A*) A general downward movement which starts soon after the construction and is preceded by an upward movement as described in Chap. VII, par. 27. This downward movement tends to become slower as the time goes on, but it may be years before it ceases.

(*B*) A seasonal fluctuation which may mask, and even reverse for a time, the general downward trend. The tunnel generally rises in the summer and falls during the winter. The period of this movement is one year from peak to peak and it is never ceasing.

(*C*) A tidal fluctuation which makes the tunnel rise with a falling tide and fall with a rising tide. The period of this movement is of the same length as the tidal period and these fluctuations never cease.

(*D*) A change due to sudden changes in the superimposed load.

35. General Downward Movement.—The general downward movement can be explained by leakage which removes some water and possibly even silt from below the tunnel and thereby causes

it to settle. This action may be compared with that in a hydraulic jack in which the plunger has been forced up under pressure of water, and the water connection closed. If the plunger is absolutely tight it will remain in its original position, but if there is a leak, it will gradually drop. In the tunnel the settlement is greatest before the tunnel is waterproofed, because the leakage then is heaviest. After the tunnel has been waterproofed and made as nearly watertight as a tunnel can be made, the downward movement will diminish, and as a tunnel generally gets tighter as time goes on, the settlement will gradually decrease. The settlement may be expected to cease when the leakage into the tunnel becomes so small that the natural supply of water to the silt can keep pace with the leakage, or when all the silt below the tunnel has lost its surplus water. Unless the depth of silt below the tunnel is small, the former condition will prevail.

36. Seasonal Fluctuation.—The seasonal fluctuations can be determined only by observations extending over years. The crest occurs in August, September or October and the trough in February, March or April. These times correspond with the periods of maximum and minimum temperatures of the ground. It has been thought, therefore, that the fluctuations are caused by the temperature changes; this is doubtful. It is possible that they are due to seasonal changes of the depth of the river bed, however these may be caused. The real cause is as yet unknown.

37. Tidal Fluctuations.—The tidal fluctuations are caused by the changes of the superimposed load producing a change in the volume of surplus water in the silt below the tunnel. Hence the tunnel is low at high tide and high at low tide, and the changes are proportional to the height of the tide. It is worth noting that even in the stiff London clay small tidal changes in elevation and in shape have been observed. The range of tide in the River Thames is about 20 ft.

38. Movements due to Change in Superimposed Load.—If changes are made in the superimposed load, such changes will produce a movement of the tunnel. For example, if the waterway is deepened, the load above the tunnel is decreased and the tunnel will show a corresponding rise.

39. Summary of Vertical Movements.—Not considering the movements mentioned in the last paragraph, the vertical movements of a tunnel in Hudson River silt may be summarized as follows. The first long drawn out downward movement may

be represented by a curve as shown in Fig. 138. This settlement may be about 3 in., although it varies from place to place. The seasonal fluctuations may be represented by a curve as shown in Fig. 139 and the amplitude may be expected to be about

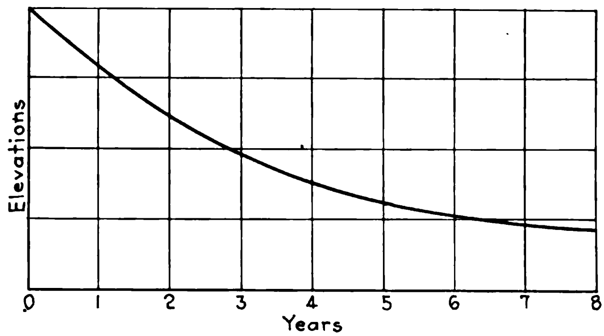


FIG. 138.—General downward movement of shield-driven tunnel in mud. This movement becomes slower and slower as years go by.

¼ in. Finally, the tidal fluctuations may be represented by a curve as shown in Fig. 140; the amplitude is about ⅛ in. These movements are all going on together and the result is represented by a curve as shown in Fig. 141. The full line

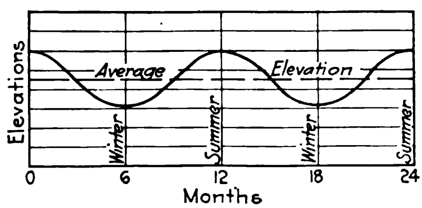


FIG. 139.—The seasonal fluctuation in elevation of a shield-driven tunnel in mud.

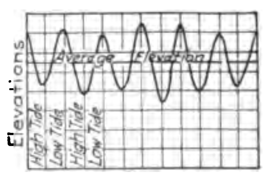


FIG. 140.—The tidal fluctuations in elevation of a tunnel in mud under a tidal waterway.

indicates the actual changes and the dotted line the average movement. This diagram indicates the importance of knowing the separate phases of movements in order to interpret the observations properly. If for example, the initial elevations are taken at the time *AA* and no further levels are taken until *B* is reached, the inference will be that the tunnel has settled from *AA* to *B*, whereas, looked upon as a long time operation, it really has settled only from *A* to *B*. If levels are run at the time

CC and then at *DD* the inference would be that the tunnel was rising, although looked upon as a long time operation, it has settled from *C* to *D*. Unless the observations are made at regular intervals for a period of several years, a true picture of what is happening cannot be obtained.

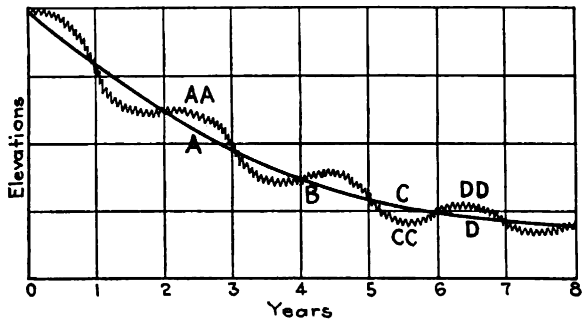


FIG. 141.—This represents the combined fluctuations in elevation of a tunnel driven in mud under a tidal waterway.

40. Stability of Pennsylvania Railroad and Hudson & Manhattan Railroad Tunnels in Silt.—The Pennsylvania Railroad Company has made exact surveys at monthly intervals of its tunnels crossing the Hudson River (A-18) from the date they were opened for traffic (November, 1910) to the present time (August, 1922). The portion of these tunnels between the river lines is in Hudson River silt and the surveys here show that up to 1917 a gradual general settlement occurred, amounting to an average of 1¼ in., but that since then no general settlement has taken place. The seasonal fluctuation of elevation has continued throughout the whole period and has averaged 5/16 in. and the tidal fluctuation has also continued, the average being rather less than ⅛ in. The leakage diminished from 650 gal. (U. S.) per tunnel per 24 hr. in 1910 to 250 gal. in 1916; since then it has remained virtually constant except for seasonal fluctuations.

The original tunnel designs included screw pile foundations at 15 ft. centers. Research by General Raymond during the construction period led to the decision to omit the piles. These continued surveys (supported by similar ones on the Hudson & Manhattan Railroad (A-17) tunnels) are most valuable. They vindicate the decision to omit the piles and prove that a properly designed and built tunnel, under heavy main line passenger and freight traffic, is stable in ground of this kind.

CHAPTER XV

WORKING FORCE, PROGRESS AND COST

A. WORKING FORCE

1. Work Carried out Intensively.—Owing to the heavy overhead charges connected with tunnel work it is usually to the interest of all parties concerned to finish the building of a tunnel as rapidly as possible. For this reason the work is generally continued throughout the 24 hours for at least 6 days a week and at as many headings as the work will permit.

2. Length of Shift.—The 24-hr. working day is divided into a number of shifts. In air of normal pressure the length of each shift depends on local usage and at the present time usually is 8 hours. When working in compressed air, however, the air pressure will determine the length of the shift. The number of hours to be worked by one man in each 24-hr. period in compressed air work is discussed in Chap. XVII. The length of the shift, or rather of the actual working time of each man is of importance, because he will be paid a full day's pay irrespective of the length of his working time.

3. Working Force.—The working force needed for carrying out the work of a single heading may be divided into the tunnel force and the surface force. The tunnel force will include the men engaged at the heading, those on transportation in the tunnel and those engaged on waterproofing, maintenance and other work below ground. The surface force includes the men handling materials in the yard, shop men and power plant men.

4. Tunnel Force.—In Table XXX is shown the tunnel force employed in a number of tunnels about which the information has been obtained. These figures are also shown plotted in Fig. 142 which shows two curves. One curve has the equation.

$$M = 4 + 0.050D^2 \qquad (47)$$

and the other

$$M = 6 + 0.075D^2, \qquad (48)$$

where M is the number of men in the tunnel force in one shift and D the external diameter of the tunnel in feet. It appears that the

number of men in the tunnel will lie usually between the limits determined by these two curves. The lower limit may be assumed where the excavation work is easy and the men skilled in their work, while the upper limit will prevail when the work of excavation is difficult or the men unskilled.

Table XXX.—Working Force in Tunnels

Ref. No.	Tunnel	External diameter, feet	Number of men per shift	Ground
(A-5)	Sarnia	21.00	50	Soft clay
(E-4)	Mersey	10.00	10	Waterbearing sand
(E-7)	Blackwall	27.00	60	Sand, open gravel
(A-12)	Chicago 39th street sewer	24.75	40	Clay
(E-17)	Rotherhithe	30.00	60	Sand, rock, clay
(A-22)	Gowanus	14.67	19	Clay
(S-5)	Dee Aqueduct	9.00	9	Sand
(A-18)	Pennsylvania R. R. Hudson River	23.00	30	Part rock, part earth
(A-18)	Pennsylvania R. R. Hudson River	23.00	27	Sand and gravel
(A-18)	Pennsylvania R. R. Hudson River	23.00	24	Silt
(A-35)	Rapid Transit, N. Y. City 60th street	18.00	26	Part rock, part earth
(A-35)	Rapid Transit, N. Y. City 60th street	18.00	18	Sand and gravel
(A-27)	Rapid Transit, N. Y. City Old Slip	17.16	32	Sand and gravel
(A-27)	Rapid Transit, N. Y. City Old Slip	17.16	28	Silt
(A-28)	Rapid Transit, N. Y. City Whitehall	18.00	35	Sand and gravel
(A-28)	Rapid Transit, N. Y. City Whitehall	18.00	23	Sand and gravel
(E-11)	Greenwich	12.75	12	Clay, sand, gravel
(E-15)	Baker St. & Waterloo	13.00	13	Sand and gravel
(E-10)	City and South London	12.50	15	Clay
(A-17)	Hudson & Manhattan	16.58	21	Silt
(A-17)	Hudson & Manhattan	16.58	28	Part rock, part earth

5. Surface Force.—It is more difficult to establish a general rule for the number of men in the surface force, because the number is affected by various independent conditions, each

peculiar to the particular piece of work. If more than one heading is served from the same shaft the number of men will be less per heading than if only one heading is worked. If the tunnel is driven under air pressure the power house force will be greater than when driven in normal air. The lay-out of the yard and the mechanical facilities provided for handling the material will affect the number of men required. If certain work of

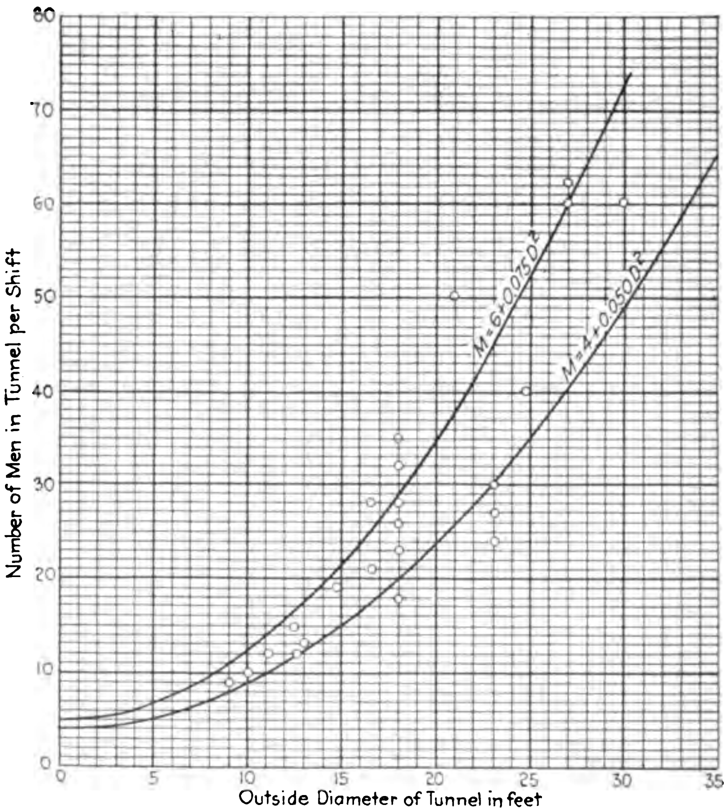


Fig. 142.—Relationship between the diameter of the tunnel and the number of men at work in the tunnel at one time. The lower curve represents the probable number when the ground is easy and the men skilled. The upper curve represents the probable number when the ground is difficult or the men are unskilled.

preparing the lining is being done at the site of the work, such as sawing timbers for wood lining or casting concrete blocks, this also will affect the size of the surface force. Generally speaking, however, it may be assumed that if no additional work is being

done in the yard beyond that of handling the materials and running the power plant the surface force will lie between the same two limits as the tunnel force, as plotted in Fig. 142.

6. Saw Mill Force.—An example of the additional force needed for sawing lumber for wood lining may be taken from that used on the Lawrence Avenue Intercepting Sewer, Chicago (A-23). This tunnel was built with a primary lining of wood and had an outside diameter of 20 ft. According to *Engineering & Contracting* of Feb. 6, 1907, a gang, consisting of 1 foreman, 1 engineer, 2 sawyers, and 4 laborers, prepared the wood for 42 lin. ft. of tunnel per day, enough for the two headings driven.

7. Concrete Block Force.—For casting concrete blocks, the force used on the Cleveland New Water Intake Tunnel (A-26) may be taken as an example. The work of making the blocks for the tunnel lining was divided into three shifts. The first shift consisted of 34 men, the second of 2 and the third of 20 men.

B. PROGRESS

8. Definition of Progress.—By the word "progress" here is meant the length of tunnel completed in a given period of time. In the following the progress is expressed in linear feet per month of 25 working days.

9. Variation in Progress.—In any tunnel the progress varies from month to month. Generally it is slow for the first month or two. This is natural, because it takes some time to organize the work, become acquainted with its conditions and acquire skill and proper team work. Then perhaps the work will progress for a while at a good rate, only to drop back again for a time, followed perhaps by a month or two of excellent progress. This variation will continue to the end of the work.

10. Causes of Variations.—The ideal would be to maintain the maximum rate of progress throughout the work, and it is worth while, therefore, to consider the causes which produce a lowering in the rate of progress, so as to avoid them if possible. As already stated the work will be slow during the first period until it is properly coordinated.

11. Bulkheads.—If the tunnel is driven under compressed air, a slowing down may be expected in the rate of progress during the erection of each bulkhead wall. It is worth, therefore, to plan carefully the design and construction of the bulkheads, so as to reduce the delays due to this cause as much as possible.

12. Insufficiency of Plant.—Delays may occur owing to insufficiency of plant. The compressor plant may be incapable of delivering the required supply of air. This may necessitate closing down some of the headings so as to concentrate the air supply in a single heading at a time, or it may be necessary to wait until more plant can be procured, or the work may be attempted with the insufficient plant. Whichever is done, it will cause delay. Perhaps the high pressure air plant does not deliver the air for the drills at the proper pressure, perhaps the shield is not capable of doing its proper work, or the transportation system is not working at the necessary efficiency, owing to shortage of cars or to defective track; in all cases a lowering in the rate of progress will result. It is vital, therefore, to have enough and proper plant and to keep it in good working order.

13. Insufficiency of Materials.—It happens sometimes that the rate of progress is lowered by insufficiency of materials of construction. This is a condition which can be guarded against, but it is necessary to look far enough ahead to prevent its occurrence.

14. Accidents.—Delays may occur due to blows or other accidents. These delays may be eliminated to a large extent by proper planning, skilled and careful work and by efficient and suitable plant.

15. Shortage of Men or Capital.—Other delays are caused by strikes, failure to procure sufficient and skilled working force, lack of capital or similar conditions.

16. Character of Ground.—Finally the character of the ground may change as the work progresses and cause variations in the rate of progress, as will be considered more in detail later.

17. Sustained Rate of Progress.—It is apparent from the above that the rate of progress determined by dividing the number of months between the start and the finish of the work into the total length of tunnel driven does not form a satisfactory basis for an estimate of progress, because many delays may have occurred which were peculiar to that piece of work. In the following, therefore, the sustained rate of progress, or the rate of progress attained for several months, will be considered to indicate the rate of progress when progress actually was made.

18. Estimate of Time.—In order to arrive at an estimate of time for carrying out a given project, based on the sustained rate of progress, it will be necessary to add a certain length of time to

allow for the unavoidable slower rates at certain times. It is apparent that if the tunnel is short the mean rate of progress from beginning to end will be less than when the tunnel is long enough for the sustained rate of progress to be maintained for a long period.

19. Effect of Ground on Progress.—Experience has shown that the character of the ground has a profound influence on the rate of progress. In the following the rate of progress that may be assumed in various kinds of ground will be considered.

20. Average Wet Ground.—By average wet ground is meant waterbearing ground of the character of clay, sand or earth, having some cohesion; not enough to require blasting but enough to prevent excessive escape of air, and requiring excavation to be carried out in advance of the shield. Experience as to progress in this kind of material has been obtained from the following tunnels.

(*A*) Sarnia (A-5): Outside diameter 21 ft. The Sarnia tunnel was driven through soft waterbearing clay. The approaches were constructed in normal air. The average sustained progress on the Canadian approach was 250 ft. per month over a period of 7 months, and on the American side 218 ft. over the same period. Under the river where the tunnel was driven under air pressure, the average sustained progress was 364 ft. per month over 4 months on the Canadian side and 256 ft. over 3 months on the American side. The average sustained progress over the whole length was 259 ft. per month.

(*B*) Whitehall (A-28): The tunnels driven from the Brooklyn side for the greater part of their length were in fine sand and clay. For "Line C" the average sustained progress was 189 ft. per month over a period of 4 months and for "Line D" 210 ft. per month over a period of 4 months.

(*C*) Old Slip (A-27): The tunnels from the Brooklyn side were mostly in fine sand and clay. The average sustained monthly progress on "Line A" was 184 ft. over a period of 4 months and on "Line B" 186 ft. over the same period.

(*D*) Blackwall (E-7): The distance between the river shafts is 1,222 ft. For a distance of about 700 ft. the tunnel was under a cover of clay. Through this portion 611 ft. were driven in 11 weeks, making an average sustained progress of 231 ft. per month.

(*E*) Dorchester (A-34): The material through which the Dor-

chester tunnels were driven was usually medium stiff blue clay at the upper portion and a hard mixture of sand and boulders and clay at the bottom portion of the tunnel section. The sustained progress for a period of 8 months was 260 ft. per month.

(*F*) Rotherhithe (E-17): The distance between the two river shafts is about 1,510 ft. The tunnels were under a cover of mottled clay throughout, and were driven through layers of sand and clay, rock, pebbles and loamy sand. The ground was rather more open during the first than during the second half of the distance. The first half was driven in 26 weeks, during which there were some periods of delay, making an average monthly progress of 126 ft. The second half was driven at an average monthly progress rate of 236 ft.

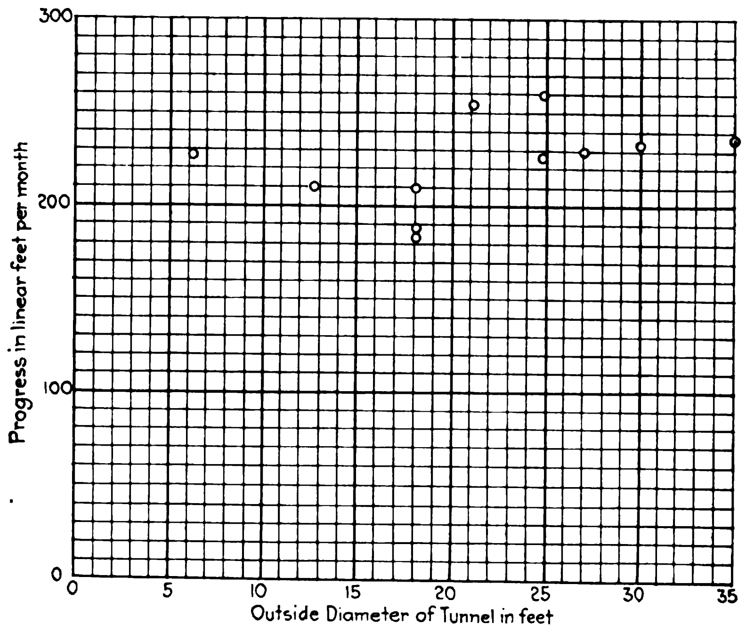


FIG. 143.—Relationship between the diameter of the tunnel and the progress in linear feet per month in "average wet ground." See Par. 20 for definition of this term.

(*G*) Greenwich (E-11): The Greenwich tunnel was for the greater part driven through close sand at the top with underlying layers of clay and sandy clay. The sustained progress for a period of 4 months was 210 ft. per month.

(*H*) Chicago 39th Street Sewer (A-12): In this tunnel, which was driven through soft clay, the average progress was 225 ft. per month.

(*I*) Providence (A-20): This tunnel was driven through dry sand and quicksand. The average progress was 228 ft. per month.

21. Progress in Average Wet Ground.—The monthly progress in relation to the external diameter of the above named tunnels is plotted as shown in Fig. 143. It is apparent that in this kind of ground the size of the tunnel has no influence on the progress and that a sustained progress of from 200 to 250 ft. may be expected.

22. Progress in Open Wet Ground.—When the ground is open the progress is rather problematic. In the Blackwall tunnel, (E-7) through the stretch where the gravel was open, the progress at times was less than 1 ft. a day or at the rate of 21 ft. per month, but at other times it reached as much as a rate of 84 ft. per month. On the Ravenswood tunnel (A-8) 98 ft. of soft ground was passed through in one month. Probably an average of from 25 to 100 ft. may be expected according to the character of the ground, and it is further probable that the progress would be less with an increasing diameter, owing to the difficulty of keeping dry the face of a larger tunnel.

23. Progress in London Clay.—Most of the tunnels driven in London clay are not more than about 13 ft. in diameter. The average progress made has been 300 ft. per month when excavation has been done by hand and 660 ft. per month when the Price excavator has been used.

24. Progress in Rock.—Rock tunneling is not carried out by the shield method except for short lengths. If the cover is sufficient the average progress may be assumed at from 75 to 100 ft. per month.

25. Progress in Rock and Earth.—When rock occurs at the lower part of the tunnel with waterbearing earth above, the progress may be assumed at from 50 to 100 ft. per month, according to the character of the overlying ground.

26. Progress in Silt.—The progress that may be made in silt varies with the diameter of the tunnel, according to indications from previous work. The average sustained progress made in the Hudson and Manhattan Railroad tunnels (A-17), which had a diameter of 16.58 ft., was 670 ft. per month, corresponding to

a tunnel displacement of 5,360 cu. yd. On the Pennsylvania Railroad tunnels under the Hudson River (A-18) the average sustained progress was 360 ft. per month, corresponding to a displacement of 5,540 cu. yd. The monthly displacement in silt, therefore, is apparently independent of the diameter and may be assumed at 5,450 cu. yd. per month. In that case the average progress may be expressed by

$$P = \frac{187,300}{D^2} \tag{49}$$

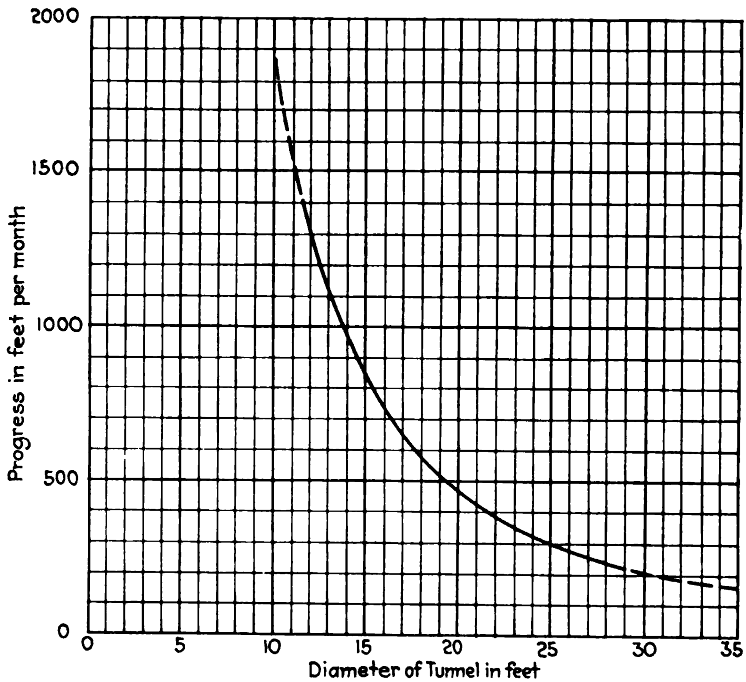


FIG. 144.—Relationship between the diameter of the tunnel and the monthly progress in mud or silt.

where P is the sustained progress in feet per month and D the external diameter of the tunnel in feet. The curve represented by this equation is shown in Fig. 144.

C. COMPARATIVE COSTS

27. Purpose and Methods of Comparison.—The purpose of considering comparative costs is to form a basis for estimating

the cost of a tunnel to be built on the knowledge gained from the cost of tunnels already built. For tunnels having the same kind of lining the comparisons may be made either for varying diameters in the same kind of ground or for a given diameter in varying kinds of ground.

28. Tunnels in London Clay.—The comparative cost of tunnels in London clay will be considered first. In this clay tunnels have been built of diameters ranging from 11 ft. 3 in. to 32 ft. The material is remarkably uniform in character and tunnels were built during a period through which there was little variation in the unit costs of materials and labor. These tunnels which are considered in the comparison were built in the period 1900–1905, and their costs are tabulated in Table XXXI.

TABLE XXXI.—TUNNELS IN LONDON CLAY. COMPARATIVE COST (Excavation and Iron Lining only)

Internal diameter, feet	External diameter, feet	Volume per lin. foot of tunnel, cubic yards	Cost per lin. foot of tunnel	Cost per cubic yard of tunnel
10.50	11.25	3.71	$ 49.21	$13.40
10.50	11.25	3.71	45.20	12.20
11.69	12.31	4.42	52.80	11.90
13.14	14.00	5.72	67.76	11.80
15.00	16.00	7.46	99.30	13.20
21.20	22.50	14.72	194.10	13.20
21.20	22.50	14.72	168.50	11.40
25.00	26.50	20.40	292.10	11.00
30.00	32.00	29.80	415.77	13.90
30.00	32.00	29.80	368.00	12.30
Average....	.....	.....	......	$12.40

This Table shows that the cost of a tunnel in this clay is proportional to the square of its diameter.

29. Distribution of Cost.—The cost of these tunnels in London clay is distributed as follows:

	PER CENT
Excavation	37.3
Cast iron lining	54.3
Bolts, nuts and washers	5.2
Grouting	3.1

In other words, the cast iron lining accounts for more than one-half of the cost. This is one of the principal causes for the consideration of other lining materials instead of cast iron.

30. Tunnels in Varying Ground.—While the tunnels in London clay provide evidence of tunnels of varying size in the same kind of material, a basis for comparing the cost of tunnels of the same size in varying ground is afforded by the Pennsylvania Railroad tunnels under the Hudson River, (A-18) built in 1904–1909, under conditions of practically stable prices for labor, materials and supplies. While the greater part of these tunnels was driven through silt, there were portions driven through various kinds of ground. Table XXXII shows the comparative costs.

TABLE XXXII.—TWENTY-THREE FEET DIAMETER TUNNEL. COMPARATIVE COST IN VARIOUS KINDS OF GROUND

Kind of ground	Cost per cubic yard of tunnel	Cost per lin. foot	Comparative cost (rock = 100)
Rock	$29.00	$447.00	100.00
Part rock, part earth	26.00	401.00	90.10
Silt, piles and rip-rap	23.00	355.00	79.70
Sand and gravel	20.50	316.00	70.80
Sand, silt and piles	18.50	283.00	63.50
Silt under land	17.00	263.00	58.90
River silt	15.75	242.00	54.20

The costs include:

Superintendence in tunnel.
Power house labor and supplies.
General tunnel supplies and tools.
Shield labor, supplies and tools.
Tunnel lighting, labor and supplies.
Transportation, including labor in tunnel, shaft and on surface, disposal (teams and dump) and supplies.
Excavation labor.
Erection labor.
Field office rentals and salaries.
Permanent lining materials (cast iron and bolts).
Contractor's headquarters salaries and rentals.
Accident compensation.
Plant depreciation.

In fact, the costs represent the direct costs to the contractor without allowance for cost of financing, risk and profit.

These tunnels were driven under an average air pressure of 25 lb. per square inch. The displacement was 15.4 cu. yd. per linear foot.

31. Distribution of Cost.—In the following Table XXXIII is shown the distribution of cost for the cases given above. This distribution is given in percentages and covers the excavation and erection of cast iron lining. It does not include calking, grummeting nor grouting.

TABLE XXXIII.—DISTRIBUTION OF COSTS

Item	Percentage of total cost in						
	Rock	Part rock part sand	Silt piles rip-rap	Sand and gravel	Sand silt with piles	Silt under land	River silt
Head office salaries	3.28	3.66	4.13	4.65	5.19	5.57	6.07
Field office salaries	7.10	4.98	3.68	4.66	2.88	2.90	2.23
Tunnel superintendence	1.57	2.85	2.95	1.41	0.90	1.65	1.05
Wages, excavation	20.30	18.90	9.35	11.42	8.77	4.98	2.81
Wages, erection of lining	3.44	2.01	5.34	1.75	2.70	3.10	3.50
Cast iron lining, materials	28.90	32.22	36.35	40.80	45.50	49.00	53.40
Plant, shield and hydraulic	3.90	4.35	4.90	5.60	6.24	6.61	7.26
Low pressure air	3.55	3.95	4.44	5.08	5.67	6.00	6.60
All other plants	1.72	1.87	2.02	2.80	3.10	2.73	3.33
Power house, wages	4.88	4.37	4.00	4.81	3.87	3.00	2.51
Power house, coal and supplies	2.85	2.89	4.63	3.32	2.20	1.94	1.42
Transportation, wages, tunnel	1.21	1.30	2.35	0.52	0.65	1.20	1.48
Transportation, wages, shaft	2.15	3.66	2.48	2.52	1.72	1.72	1.30
Transportation, wages, surface	4.62	2.85	1.77	1.70	1.68	1.49	1.43
Transportation, team, dump	2.80	2.91	3.78	2.88	3.24	3.24	1.32
Transportation, supplies	0.93	0.58	0.71	0.57	0.60	0.46	0.54
Shield and pipe lines, wages	1.03	2.12	2.58	1.20	1.18	1.43	1.02
Shield and pipe lines, supplies	0.23	0.29	0.52	0.37	0.46	0.34	0.43
Lighting tunnel, wages	1.04	1.06	0.81	0.60	0.57	0.47	0.30
Lighting tunnel, supplies	0.77	0.33	0.24	0.27	0.18	0.14	0.14
Tunnel, general supplies	2.88	1.90	1.90	1.86	1.35	0.58	0.28
Accident compensation, etc	0.85	0.95	1.07	1.21	1.35	1.45	1.58

32. Distribution of Labor Cost in Hudson River Silt.—On the same work observations of the distribution of the labor cost while the tunnels were being driven under compressed air through silt were made on two occasions. In neither case was any excavation done ahead of the shield, but the silt was allowed to flow into the tunnel in such quantities as the proper guiding of the shield

demanded. In the first case the quantity taken in was about twice as large as in the second case, thus increasing the cost of mucking. The distribution is shown in the following Table XXXIV.

TABLE XXXIV.—DISTRIBUTION OF LABOR COST IN SILT

Item	First observation, per cent	Second observation, per cent	Mean, per cent
Shoving shield	1.90	1.00	1.45
Mucking	24.30	12.40	18.35
Sending back jacks	3.60	3.50	3.55
Erecting iron lining	19.30	19.10	19.20
Bolting	12.30	24.10	18.20
Transportation	28.70	32.60	30.65
Track and staging	3.40	1.00	2.20
Hydraulic mains	1.20	1.00	1.00
Shield repairs	2.90	3.40	3.15
Pipe lines	0.00	0.20	0.10
Lighting	2.40	1.70	2.05

33. Comparison of Distribution.—In *Trans. Canadian Soc. C. E.*, vol. 28, 1914, p. 333, a distribution of cost is given of the work on the Concorde Metropolitain tunnel in Paris (F-12). This may be compared with the distribution given in the preceding paragraphs as follows:

TABLE XXXV.—COMPARISON OF DISTRIBUTION OF COST

Item	Percentage of cost	
	Concorde Met., per cent	P. R. R. Hudson River, per cent
Wages	36.6	40.4
Plant and power	20.1	18.7
Permanent lining materials	43.3	40.8

The resemblance is sufficiently close to point to a general applicability of the cost distribution given.

D. COST OF SHIELD DRIVEN TUNNELS

34. Difficulties of Comparing Costs.—Since the year 1886 shield driven tunnels have been built in many places through all kinds of ground. The prices of materials and labor have fluctuated from year to year and have been different in different countries. The design has not followed rational lines. The tunnels have been of different lengths and consequently the cost of plant has been heavier in some cases than others. Wages, which form an important item in the cost of tunnels, have changed from time to time and have not been the same at all places. Many tunnels have been built under contract, and the cost has been that determined by the successful bidder rather than the actual cost of the work. For example, the bids on the Rotherhithe tunnel (E-17) ranged from $4,660,000.00 to $9,400,000.00 and the accepted bid was $5,280,000.00. The greater number of shield driven tunnels built have been lined with cast iron. In the earlier tunnels little machining or none was done to the segments. In the later years machining has come more into general use, adding to the cost of the lining but reducing the cost of erection. In some places special facilities have been provided whereby this work has been reduced in cost, at others the cost of machining is high. These and other similar conditions make it somewhat difficult to estimate the cost of a tunnel from previous work.

35. Basis of Comparison.—In order to eliminate to some extent the yearly fluctuations of prices of materials and labor, Dun's index of wholesale prices of commodities has been used in the following for bringing the cost of a tunnel built in any given year to a standard scale of cost. The index for the year 1914 has been taken as unity, so that in order to bring the cost in any given year to the standard of 1914, the cost should be divided by the index of the year considered. This method of correction is not entirely satisfactory, because it applies particularly to the United States and does not directly take into account the changes in wages, but it is believed that it brings the cost of the various tunnels on a more equitable basis of comparison. Figure 145 shows the fluctuation of this index from 1885 to 1920, the index for 1914 being taken as unity.

36. Cost of Cast Iron Lined Tunnels in London Clay.—From figures given in Copperthwaite, pp. 367–368, for tunnels driven

through London clay it is found that the average price per cubic yard of tunnel during the period 1900–1905 was $11.50. Dun's index for this time is 0.85, so that the cost in 1914 would be $13.50 per cubic yard of tunnel, or $0.50 per square foot of internal clearance per linear foot of tunnel.

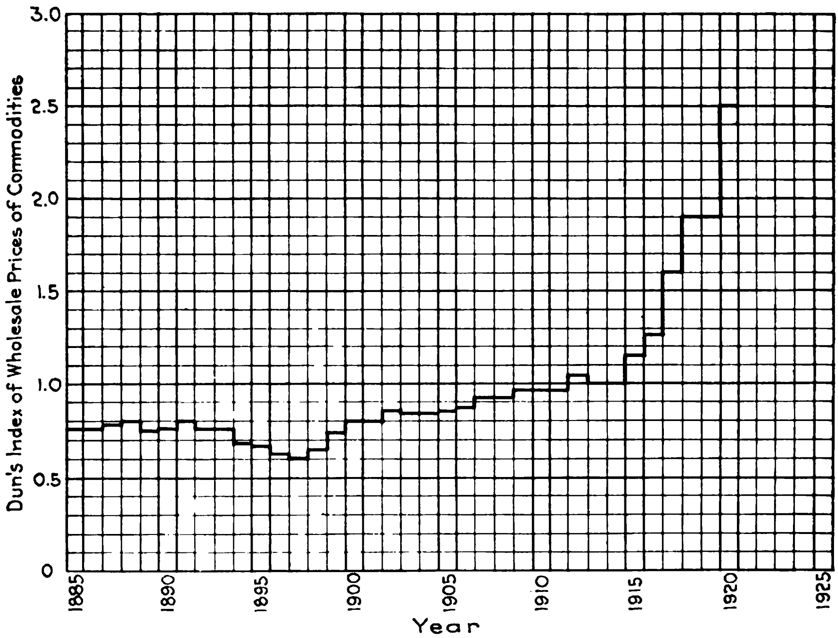


FIG. 145.—Fluctuation in Dun's index of wholesale prices of commodities from 1885 to 1920. The index for the year 1914 is taken as unity.

37. Cost of Cast Iron Lined Tunnels in Waterbearing Ground. Table XXXVI shows the cost of various tunnels driven through waterbearing ground and Table XXXVII shows the cost of the same tunnels adjusted according to Dun's index. This table indicates that in average ground the price in the year 1914 would be $36.00 per cubic yard. Under favorable conditions the price may be about 20 per cent less and if the conditions are unfavorable about 20 per cent higher. The cost per square foot of internal clearance per linear foot of tunnel corresponding to $36.00 per cubic yard is $1.57, assuming no other lining than the cast iron.

TABLE XXXVI.—ACTUAL COST OF SHIELD DRIVEN CAST IRON LINED TUNNELS

Ref. No.	Tunnel	Date	Country	External diameter, feet	Cu. yds. per lin. ft.	Cost in dollars per	
						Lin. ft.	Cu. yd.
(A-5)	Sarnia	1888	U. S.	21.00	12.83	$324.00	$25.30
(E-7)	Blackwall (heavy)	1892	England	27.00	21.20	613.00	28.90
(E-7)	Blackwall (light)	1892	England	27.00	21.20	512.00	24.10
(E-11)	Greenwich	1899	England	12.75	4.74	175.00	36.90
(A-17)	Hudson & Manhattan	1905	U. S.	16.58	8.00	292.00	36.50
(A-18)	P. R. R. Hudson River	1905	U. S.	23.00	15.39	448.00	29.20
(E-17)	Rotherhithe	1905	England	30.00	26.20	667.00	25.40
(F-12)	Concorde Metropolitain	1911	France	25.54	18.90	558.00	29.50
(A-27)	Old Slip	1914	U. S.	17.16	8.60	409.82	46.50
(A-28)	Whitehall	1914	U. S.	18.00	9.43	338.70	35.90
(A-30)	14th Street	1914	U. S.	18.00	9.43	341.75	36.20

TABLE XXXVII.—ADJUSTED COST OF SHIELD DRIVEN CAST IRON LINED TUNNELS

Ref. No.	Tunnel	Date	Index	Adjusted cost per		Remarks
				Lin. ft.	Cu. yd.	
(A-5)	Sarnia	1888	0.79	$410.00	$31.90	Easy ground
(E-7)	Blackwall (heavy)	1892	0.75	657.00	38.50	Part average, part bad
(E-7)	Blackwall (light)	1892	0.75	683.00	32.20	Average ground
(E-11)	Greenwich	1899	0.76	230.00	48.50	Average
(A-17)	Hudson & Manhattan	1905	0.84	348.00	43.50	Some bad, some good
(A-18)	P. R. R. Hudson River	1905	0.84	534.00	34.70	Mostly good ground
(E-17)	Rotherhithe	1905	0.84	794.00	30.30	Good ground
(F-12)	Concorde Metropolitain	1911	0.97	575.00	30.40	Average ground
(A-27)	Old Slip	1914	1.00	409.82	46.50	Some bad ground
(A-28)	Whitehall	1914	1.00	338.70	35.90	Average ground
(A-30)	14th Street	1914	1.00	341.75	36.20	Average ground

38. Cost of Wood and Cast Iron Lined Tunnels in Dry Ground Compared.—The Lawrence Avenue intercepting sewer in Chicago, (A-23) built in 1906, furnishes an example of a tunnel driven by shield through dry clay, lined with wood and having a secondary lining of brick. The cost was $79.75 per linear foot. The outside diameter was 20 ft. and the inside 16 ft. The cost per cubic yard was $6.83, or adjusted for 1914 prices $7.75. The cost per square foot of internal clearance per linear foot of tunnels amounts to $0.29, compared to $0.50 for cast iron lined tunnels. The example indicates, as might be expected, that in dry ground a wood and masonry lined tunnel will be more economical than one lined with cast iron, although the cost in this case appears low.

39. Cost of Wood and Cast Iron Lined Tunnel in Wet Ground Compared.—As an example consider the Dorchester tunnel at Boston (A-34) in comparison with the Whitehall tunnel at New York (A-28) the contracts for both of which were let in 1914. The Dorchester tunnel has an outside diameter of 24.16 ft. and an inside diameter of 18.67 ft. The Whitehall tunnel has an outside diameter of 18 ft. and an inside clearance diameter of 15.50 ft. The cost per cubic yard of tunnel for the Dorchester tunnel was $35.94 and for the Whitehall tunnel $35.90, in other words the cost per cubic yard displaced was practically the same. Comparing the cost per square foot of internal clearance per linear foot of tunnel, the result is different. This was, for the Dorchester tunnel, $2.23 and for the Whitehall tunnel $1.80. For useful area, the cast iron lined tunnel in waterbearing ground appears to be more economical than the wood lined. The evidence, however, is not conclusive, and in many cases it would be worth while to obtain bids for both kinds of lining.

40. Cost of Steel and Cast Iron Lined Tunnels Compared.—In comparing structural steel and cast iron lined tunnels there is no available evidence of existing tunnels to use for comparison. For the same internal clearance, however, tunnels with these linings will have the same external diameter, so that the comparative cost will depend entirely on the cost of the lining. The weight of the cast iron lining will be from 2½ to 3 times as great as that of the steel lining, while the cost per ton of steel usually will be less than twice that of cast iron, indicating a definite saving in the use of structural steel. This saving will be more marked in large than in small diameter tunnels. At places where the item of transportation is a factor the lighter weight of the steel lining will cause a further saving in cost. Within the structural steel would be placed a concrete lining.

41. Comparison of Cost of Tunnels Driven with and without Shield.—A comparison of the cost of tunnels driven with and without shield can be made only in such cases where it is possible to drive a tunnel without a shield. Generally speaking it is limited, therefore, to tunnels in dry ground and to such cases in waterbearing ground where a tunnel may be built by a trench method.

42. Tunnels in Dry Ground—As an example for comparison of tunnels driven in dry ground the Blue Island Avenue tunnel

of the Chicago water works system may be taken. This tunnel was put under contract in the year 1906 at a cost of $19.70. per linear ft. Its outside diameter is 9 ft. 8 in. and its inside diameter 8 ft. The cost per cubic yard displaced was, therefore, $7.25 or corrected for 1914 prices, $8.35 per cubic yard, compared with $7.75 (see par. 38) for a tunnel driven with shield. This comparison indicates that there is not much choice, when the ground is suitable for excavation without shield, between the work being done with or without shield.

43. Tunnels in Waterbearing Ground.—In *Proc. Inst. C.E.*, vol. 185, it is stated that in the construction of the Detroit tunnel the various methods of construction used gave costs as follows:

Trench and tremie method, normal air...	$332.00 per linear foot of track
Side shields, normal air..................	$228.00 per linear foot of track
Side shields, compressed air..............	$257.00 per linear foot of track

These figures indicate that the use of shield is more economical than the trench method. This is further indicated by the cost of the Harlem River tunnels built by trench method in 1911–1912. The contract price was $375.00 per linear foot of track, or adjusted to 1914 prices, $391.00 per linear foot of track. The tunnels under the East River built by the shield method in 1914–1916 were constructed at a cost of $363.00 per linear foot of track.

TABLE XXXVIII.—COST OF SHIELDS

Ref. No.	Tunnel	Year	Index	Cost	Adjusted cost, C	Diam. D, feet	$\frac{C}{D^2}$
	London tube.......	1900	0.80	$2,180	$2,730	12.00	19.0
	London tube.......	1900	0.80	7,800	9,650	16.00	37.6
	London tube.......	1900	0.80	11,700	14,600	22.00	30.2
(E-11)	Greenwich.........	1899	0.75	11,400	15,300	12.75	84.0
(E-7)	Blackwall.........	1892	0.75	48,600	64,700	27.00	89.0
(A-19)	P. R. R. East Riv..	1904	0.85	44,000	51,800	23.00	98.0
(A-18)	P.R.R. North Riv.	1904	0.85	44,000	51,800	23.00	98.0
(A-23)	Lawrence Ave., Chicago..........	1906	0.87	8,000	9,200	20.00	23.0
(A-17)	Hudson & Manhattan..............	1903	0.85	26,000	30,600	16.58	111.0
(A-17)	Hudson & Manhattan..............	1904	0.85	18,500	21,800	16.58	79.0
(A-16)	Battery...........	1901	0.80	20,000	25,000	16.58	90.0

44. Cost of Shields.—Table XXXVIII shows the cost of various shields.

From this table it appears that in dry ground the cost of a shield in dollars may be assumed to be, at 1914 prices, from 20 to 30 times the square of the diameter of the tunnel in feet and in waterbearing ground about 90 times.

45. Cost of Plant.—As an example of the cost of plant for a shield driven tunnel under compressed air the cost and distribution of cost of the plant for the Battery tunnels (A-16) are shown in Table XXXIX. These tunnels were built in 1901, so that for 1914 prices the total cost of the plant would be $504,000.00.

TABLE XXXIX.—COST OF PLANT. BATTERY TUNNELS (A-16)

Item	Cost	Percentage
Power plants	$195,000	46
Shields	80,000	19
Tunnel plant, except pumps	84,000	20
Tunnel pumps	9,000	2
Surface and yard plant	25,000	6
Cars	11,500	3
Teams and wagons	5,000	1
Rails	3,500	1
Machine shop	3,000	1
Dock	4,000	1
Total plant cost in 1901	$420,000	100

The plant was distributed at both sides of the river and served four headings. The total length of tunnel was 14,372 ft. making the cost of the plant $35.00 per linear foot of tunnel or $4.38 per cubic yard of displacement.

CHAPTER XVI

SURVEY

INTRODUCTION

1. True Alignment Necessary.—The work of the surveyor in tunnel construction has peculiar importance as compared with that work in many other lines of construction. The reason for this is that it is not possible to judge the correctness of the work simply by eye as is possible to a large extent with works built on or above the surface of the earth. A tunnel may be started at one end and driven to its other end. Its alignment cannot be judged by eye until it arrives there. Ot it may be started from two points far apart and driven to a junction somewhere between the two points. The meeting must be accurate and there is nothing to ensure this except care and skill in the survey.

2. Purpose of Chapter.—It is the purpose of this chapter to outline the special surveying methods and appliances which have been found useful in shield tunnel work.

3. Work of Surveyor.—The surveyor's work will be described. in the following under these heads:

(*A*) The preliminary survey.

(*B*) The sub-surface exploration.

(*C*) The precise surface survey.

(*D*) The transfer of the working line and level from the surface to the tunnel.

(*E*) The carrying forward of the line and level in the tunnel.

(*F*) The checking of the position of the shield and the tunnel with respect to the true line and level.

(*A*) THE PRELIMINARY SURVEY

4. When Maps Are Obtainable.—In well settled districts or large towns accurate official maps are to be had. A few check measurements may be made on the ground to make sure that no serious error exists. This proved, the line of the proposed tunnel is laid down on the map and a profile drawn from the elevations

on the map. This will give a fairly correct ground work for a preliminary estimate of the quantities of work involved and the consequent probable cost. This outline sketch will enable the engineer to decide where to place the borings he must make for the exploration of the sub-surface conditions.

5. When Maps Are Not Available.—Where no survey maps exist, a preliminary survey of the terrain must be made. Ordinary survey methods will be used and that most suitable for the country and the men available will be chosen. What will be sought at this stage is not high accuracy so much as a rapid taking of the topography on which to base an outline plan of the project and a means of placing the borings, test pits and other exploration work.

(*B*) THE SUB-SURFACE EXPLORATION

6. Necessity for Explorations.—The need of thorough exploration of the ground through which the tunnel must be bored cannot be over-stressed. The tunnel must be built far out of sight, buried deep in the earth. In order to escape avoidable difficulties and dangers and to afford a basis for a rational design of the structure it is imperative to have the fullest knowledge of the ground that will be penetrated. Whether it is possible to build on alternative lines and gradients, or whether it is impossible to make any choice, it is equally vital to know the character of the ground.

7. Borings.—The exploration will be made largely by borings. The first problem will consist of deciding how many borings to put down, where to put them and what sort of borings to make. These questions depend on the general geological features of the territory and on the knowledge of and experience with these features which are available. Some tunnels are projected in places where the geological conditions are plain and simple. Of these London is an example. On the other hand, the geological structure may be complex and involved. New York is an example of this condition.

8. Geological Maps.—Official geological maps and publications should be studied and care be taken to see whether faults, contact zones or other possible sources of trouble are shown.

9. Consultation of Geologist.—The retention of the geologist best qualified by his local knowledge to act as adviser to the

engineer is often an investment that will pay heavy dividends in the avoidance of trouble.

10. Result of Change of Location.—Sometimes a moderate lateral or vertical shift in the location of the tunnel may result in the escape of great difficulties in the construction and every means available should be exhausted so that the best construction conditions are afforded.

11. General Scheme of Borings.—Using the preliminary survey as a basis, the engineer will draw up a general scheme for the borings. These will lie along the route or routes tentatively chosen for the tunnel. The depth of the borings should be at least to the bottom of the proposed tunnel. The spacing of the holes depends on circumstances. If the formation is uniform throughout the length of the tunnel two or three borings may be enough in a mile. If the formation is complex, severely folded, faulted, fissured, of rapidly varying elevation, or passing from one formation to another it will be necessary to space the borings at such close intervals that a fairly complete picture is obtained of the ground penetrated. The advice of a trained geologist is priceless in such a situation. The original lay-out of borings may need radical revision and other borings, between those originally laid out, may have to be made. If a boring gives a core of a certain geological formation and the next boring one of another an attempt should be made to find the line of contact between the two formations and to learn whether this contact is a simple one or whether there has been a breaking down of the rock structure.

12. Borings to be Made off the Line of Tunnel.—If the proposed tunnel is to be driven under compressed air or under a waterway the borings should be placed outside of the line of the tunnel so that the bore holes, when passed by the tunnel, will not give rise to the escape of the compressed air and possible blows. If they are placed in the path of the tunnel they should be refilled with cement grout to obviate this danger.

13. Making Borings.—The borings may be made by the engineer with his own drilling rig manned by a crew engaged by him, or the work may be done by a drilling contractor. The latter is the better course provided the terms of the contract are such that the work is completely at the control of the engineer. He must be represented at the drilling every moment of the time by a skilled inspector to verify the depths made, to collect and

store in proper core boxes the samples brought up and to keep a detailed log of each hole referenced accurately for the elevation of every change in the material penetrated so that the information may be of the maximum value.

14. Core Borings.—Where rock is met in the zone through which the tunnel will pass the diamond or shot drill should be used. Sometimes it is thought that satisfactory information is given by wash borings. These give at best only negative results. If such a boring strike a boulder no further progress can be made. All that is known is that something hard was struck. This may be bed rock, a boulder or some hard foreign substance. It is the path of prudence to use a method that will penetrate such materials and bring up cores so that no doubt may exist.

15. Borings from Scows.—For tunnels crossing waterways some of the borings will have to be made from floating scows. In waterways crowded with shipping or with strong currents this work is hazardous and tedious. It must not be shirked on this account, but every effort bent to learn the character of the bed of the waterway down to the level of the bottom of the future tunnel. Under-water borings are made by driving or washing down a casing pipe of a diameter of 6 to 10 in. The top of this casing is always above high water and it is driven down to and through any soft material in the bed of the waterway. When a hard substance is reached the foot of the casing is landed as firmly as possible and the core boring carried on within its protection. If the hard substance proves a boulder, it is drilled through, a smaller pipe, inserted within the original casing, is driven through the boulder and washed down until another hard object is reached. This process is continued until the boring reaches below the bottom of the proposed tunnel.

16. Hazards.—Sometimes the casing is carried away by a vessel colliding with it or with the drill scow and this throws away a lot of valuable work and time. There is nothing to be done but to set to work again and repeat the boring.

17. Profile of Borings.—When all the borings have been made a geological profile is drawn showing the different materials penetrated at each boring. On this profile the tentative profile of the tunnel is laid out. A study of this may result in a change of the position of the tunnel.

18. Additional Borings.—If a change is made large enough to carry the tunnel outside the zone covered by the borings, fresh

exploration work should be made. One can jump out of the frying pan into the fire.

19. Exhibit of Borings to Contractor.—It is usual to exhibit to the contractors bidding on a tunnel work the samples or cores, which have been taken as well as the drawings showing the materials met in each hole. The geological profile made from the borings should not be exhibited to the bidders. Nothing should be shown except the results obtained at each boring and these should be given merely for what they are worth and without any guarantee, implicit or explicit, as to their accuracy.

20. Soundings.—For tunnels crossing bodies of water a series of soundings at perhaps 25-ft. intervals should be taken covering a strip from 500 to 1,000 ft. wide on either side of the future tunnel. This will determine the depth of cover over the structure and enable future soundings made during and after construction to detect any lowering of the river bed due to blows or dredging, any raising due to shoving the shield blind or any other deformations and will be of use in determining what area to cover with a blanket of clay if such is required. Ordinary sounding methods will be used and no description of these will be attempted here.

(*C*) THE PRECISE SURFACE SURVEY

21. Object.—The object of the precise survey is to provide the basis for the final design of the tunnel in respect to its line and gradients and to afford the means of driving it so that when built its position will be that designed.

22. Conditions of Survey.—With shield driven tunnels there will be two main kinds of survey presented: (*a*) Where the streets of a town have to be followed and (*b*) where a body of water has to be crossed.

CASE (*a*) THE TUNNEL FOLLOWING THE STREETS OF A TOWN

23. Method Used.—The system usually followed is to use a published map of the streets on as large a scale as it is possible to get and on this map to lay out a series of traverse lines following the general course of the tunnel. The intersections of the traverse lines are scaled from the map, taking distances from street corners or other objects which can be located on the ground.

A corps then goes out with these notes and establishes the intersection points on the ground. It may be found that some of the points are not in the most convenient place and these are shifted until the best position is found. A monument is established at each intersection and a traverse run from point to point, measuring the length of each line and the angle of each intersection. The topography is taken at the same time by offsets or triangles from the traverse lines to the building lines, curb lines and other fixed objects on the street.

24. Center Line of Tunnel.—The traverse lines may or may not follow the center line of the tunnel. If they do not the intersecting points of the tunnel center line are computed from the traverse lines. When this has been done the intersection points of the tunnel center line should be laid out on the ground and the distances between them taped and the angles of intersection read as a check on the computations. With tunnels following the streets the shafts will not be much further apart than half a mile or so as a rule and consequently the degree of precision need not be so high as when a large body of water perhaps a mile or more in width has to be crossed. Nevertheless a good deal of care has to be used.

25. Measuring Line.—All lines should be taped both forward and backward and repeated if a discrepancy of over 0.01 ft. is found. Corrections for temperature and slope and for error of the tape should be applied. It is stated by Lazarus White (*Trans. Am. Soc. C. E.*, vol. 75, p. 108) that in crowded streets an average of 2,500 ft. of line and a maximum of 4,500 ft. can be taped in one hour. Angles should be read by a series of successive additions followed by reversals, with at least two independent observers.

26. Leveling.—The leveling work is simple and consists in running from the nearest established bench mark to the line of the work and taking an elevation at each tape end position. The usual precautions for fairly accurate topographical work have to be taken. The established bench mark should be checked also from other established bench marks, as in some cases a displacement may have occurred. In crowded streets it will be found convenient to do most of the work at night or early in the morning, before the traffic gets heavy.

27. Reference Marks.—All monuments must be referenced fully by measurements to fixed structures so that, in case they are

disturbed by repaving or other cause they may be re-established in the same exact position. Remember that tunneling may cause movements of the surface. Reference points must be so far away from the line of the work that they are outside of the zone of possible movement during construction.

CASE (b). THE TUNNEL CROSSING A WATERWAY

28. Triangulation.—When the tunnel line crosses a waterway the necessity arises for a triangulation. In Fig. 146 the line *A-B* represents the center line of a tunnel which has to be driven across a waterway. It is not possible to measure directly across the waterway from *A* to *B* and, therefore, a measured base

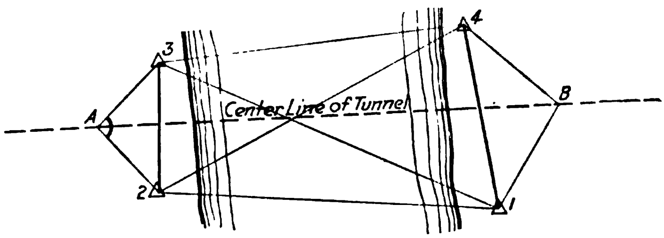


FIG. 146.—Diagram of triangulation to establish the center line of a tunnel crossing a river or waterway.

line has to be laid out along each shore as at 1-4 and 2-3. The terminal points of these base lines being mutually visible, the contained angles of the quadrilateral 1-2-3-4 can be read and consequently the lengths 1-2 and 3-4 can be computed. This network forms the basis for a complete topographical survey across the waterway. The center line of the tunnel, being marked on the ground on each side, can be tied into the base lines, and a supplementary triangulation will give the length between *A* and *B* and the direction of the line *A-B* with reference to the lines 1-4 and 2-3. The case presented is the simplest possible and supposes that all the points marked are mutually visible and can be reached by direct lines on the ground. Such conditions seldom will be found.

29. Observation Towers.—Much ingenuity often has to be exercised in the choice of the base line terminals so that the other observation points are visible from them. Sometimes the terminal points are transferred to observation towers, that is to say, the terminal point having been marked out on the ground with

permanent monuments, a timber or steel frame tower is erected over it. These towers are made double, one tower within another. The outer tower supports the observer, the inner the instrument. The construction must be most rigid to obviate vibrations, which will occur to some degree in any case. The position of the monument is transferred to the table which supports the instrument by means of two series of transit observations made at right angles to each other.

30. Stations on Roofs of Buildings.—Sometimes in built up towns even such towers are not possible and the triangulation stations have to be placed on the roofs of buildings. This makes

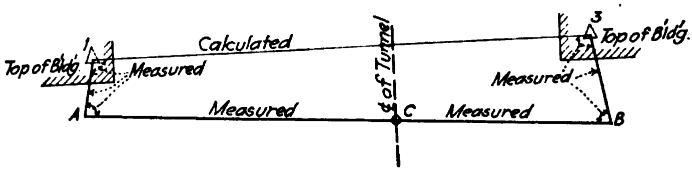


FIG. 147.—Method used when the triangulation stations are on the roofs of buildings.

it impossible to measure directly the distance between the terminal points. This has to be obtained by a secondary triangulation, based on a measured distance made on the ground as conveniently as possible to the two points on the buildings, as shown in Fig. 147. The distances 1-*A* and 3-*B* are measured.

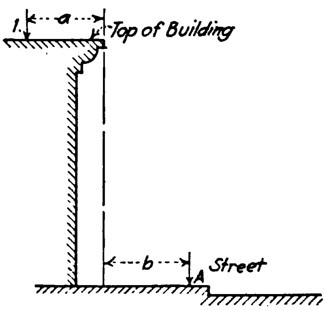


FIG. 148.—Method of connecting points on roofs with points in street.

This may have to be done in two sections *a* and *b* as shown in Fig. 148. In this way a quadrilateral is set up, 1-3-*B*-*A* in which three sides and four angles may be observed and consequently the fourth side 1-3 which is the base line may be computed. The intersection of the tunnel center line as laid out on the ground with the secondary base line is monumented as shown at *C* on Fig. 147, the distances *A*-*C* and *B*-*C* measured and the angle at *C* measured. This ties in the stationing of the tunnel center line with the triangulation.

31. Length of Base Line.—The lengths of the base lines and their general position with reference to one another must be chosen carefully so that the whole quadrilateral system is well proportioned, otherwise the calculated distances will be unreliable.

32. Precise Triangulation.—The matter of precise triangulation is not a matter special to tunneling and anyone entrusted with such a survey is certain to be already a surveyor of skill and experience, fully posted as to the principles of such work.

33. Measurement of Length.—The instrument used for measurement of length is a steel tape, 100 ft. long, graduated to one-hundredth of a foot. Tapes of 200 ft. have been used in rare cases. A monument is established at each end of each base. This monument is made of a small cylinder of non-corrosive metal, such as brass, marked with a small center punch or with fine cross-cut lines. The monuments must be entirely rigid and immovable and the details of their construction will depend on where they are. If in solid rock the cylinder is grouted into a drill hole. If in soft ground a large concrete pier may have to be built to insure stability. The monuments having been set the distance is measured between them. This distance has to be the horizontal distance and therefore, unless the two observation points are at the same elevation and the intervening ground is level, this measurement cannot be made directly on the ground.

34. Method of Measurement.—One method of doing this measuring work is as follows: First a line of stakes is ranged out by transit along the course of the base line. The stakes are long enough to be perfectly rigid in the ground and are at a distance apart slightly less than the length of the tape used, for example, if the tape is 100 ft. long the stakes would be about 98 or 99 ft. apart. Into the tops of these stakes small copper tacks are driven and marked with a fine knife-cut cross. No attempt is made to set the tacks at regular distances apart. More accurate results are secured when the intervals are at random. A heavy "trivet" or three-legged "spider" is set over the monument points by cutting-in with two transits. A mason's line is then stretched taut over the tops of adjacent stakes and tape supports placed on the line at 20-ft. intervals. The tape support consists of an iron rod or picket which can be driven into the ground. On this rod slides a movable piece which can be clamped at any

desired height. This movable piece carries a hook in which the tape rests. If the work is on the sidewalk of a city street into which pickets cannot be driven the uprights are supported on heavy flat platforms. After the mason's line has been stretched the sliding bar of each tape support is set at the height of the stretched line. Elevations are then taken on each end spider to enable the correction for the slope to be made.

35. Taping.—The tape is supported on the hooks. The rear end of the tape is attached to a wooden or metal frame anchor held rigid by the weight of a man of the survey party, known as the anchor man. The forward end is attached to a spring balance held by another man. This man puts tension on the balance. When the standard pull on the tape (usually 12 lb.) is registered the balance holder signals and the readings are taken simultaneously at both ends at the cross cut on the copper tacks on the stakes. The difference between the readings is the distance between the stake points. The temperature is taken at the middle of each tape length so that the temperature correction can be applied. The tension is sometimes placed on the tape by means of a lead or iron weight. A cord is attached to the weight, passes over a pulley of large diameter and low frictional resistance and thence to the end of the tape. An inverted bicycle wheel mounted on an iron frame makes an excellent device for this purpose.

36. Alternative Method.—An alternative method has been used. In this no intermediate stakes are set on the base line, but movable stations, called spiders, are used. These consist of a heavy iron trivet, surmounted by a brass cap having a convex upper surface on which is cut a fine cross mark. These spiders are lined in on the base line at the same distances apart as the intermediate stakes would be. The procedure is that the spiders are lined in to temporary marks previously set at intervals of slightly less than the length of the tape. The end standards and intermediate supports are then set and adjusted to grade with the top of the spiders. The tape is stretched over the support under the pull of the tension weight and just touching the brass caps of the spiders. An observer is at each spider while the chief of the party stands near the mid point of the tape. The tape is shifted and the two observers take simultaneous readings on the cross marks. The observations for slope and temperature are taken.

37. Readings Repeated.—The tape readings are repeated in order to get a high degree of accuracy. The tape should be shifted lengthwise a short distance after each reading to eliminate errors of graduation. At least five consistent readings between each pair of stations should be taken and for long tunnels the number of readings may be increased to fifteen.

38. Precision Obtainable.—To show the degree of precision obtained by these methods it may be said that in one case where five readings were taken it was computed that the probable error was 1 in 218,000, while in another case where the readings were repeated 15 times, the computed probable error was 1 in 700,000 while that of the adopted mean distance was 1 in 1,600,000.

39. Use of Plumb-bob.—It will be noticed that in both these methods the use of plumb-bobs for obtaining the distance between stations is obviated. Good results can be obtained, however. by their use. In this case one end of the tape is anchored and the other is subject to the standard tension. The tape is supported by intermediate adjustable supports as before. An observer with a plumb-bob is stationed at each station point and simultaneous readings are taken where the line of the plumb-bob intersects the tape. A base line of 2,300 ft. measured this way and with 15 repetitions for each reading gave a result which differed by not quite three-hundredths of a foot from the method without the plumb-bob. As the gear which does away with the plumb-bob is so simple and inexpensive it is better to use it than to use the plumb-bobs which are unhandy and aggravating things to use with high accuracy.

40. Standard Temperature.—The taped distances are corrected for slope and for variations of temperature from that at which they have been standardized. In the United States the temperature at which steel tapes are standard is 62 deg. F. and a coefficient of expansion of 0.0000063 is used to correct for other temperatures. That the correction is important is clear when it is stated that the correction for a variation of 110 deg F. in length of a 100 ft. tape would be 0.07 ft. Tapes of "Invar Steel" may be obtained. The coefficient of expansion of this metal is so low that under the ordinary range of temperature no correction on that account is needed.

41. Standard Tension.—Tapes are also standard for some stated tension for each tape. It is usually 12 lb. Hence the

necessity of providing a means of controlling this tension in base line work. The method of applying tension by means of a weight is probably better than that by means of a tension balance as it is steadier.

42. Standardization of Tape.—The National Bureau of Standards, at Washington, D. C. will furnish for a small fee, a certificate of comparison with standard length. It is proper to obtain such a certificate for any work of importance and in fact there should be at least two such tapes secured, one of which will be in field use while the other will be kept for testing the working tape after each run.

43. Measurements Run at Night.—Base line measurements should be made at night because the fluctuations of temperature are less and because there is less distraction and less chance of disturbance. If not at night they should be made on a cloudy day. For base lines of the usual length one night is enough time to make one set of measurements, taking fifteen readings on each tape length. The run should be made five or six times to obtain a satisfactory mean value and it is preferable to have half the runs made by one corps and half by another to eliminate or counteract personal equations.

44. The Measurement of Angles. Instruments Used.—Transits having circles of from 6¼ in. to 7 in. diameter and with verniers reading to 10 seconds of arc are used to measure the angles. For this work and for the work in the tunnel also there should be no vertical hair in the transit. Two hairs crossing diagonally are the best. Short distance sights are taken on ordinary round or octagonal sighting poles. Long sights are taken on flat target rods. A convenient form is a board 6 in. wide and 6 to 10 ft. long painted with red or black diamonds on a white ground.

45. Methods of Ensuring Accuracy.—The angles must be read in such a way that errors of observation and of graduation are reduced to a minimum. This is achieved by having several observers take the readings independently and by a system of successive additions and subtractions in the turnings. Three methods may be described.

46. First Method.—A random setting of the vernier is made and the angle repeated 20 times from left to right reading the 5th, 10th and 20th repetition. The direction of the readings is then reversed and the angle turned 20 times as before. The

final position should agree with the initial reading. If this is not the case, the mean between the initial and final readings is computed and the sum of the angles divided by 20 taken as the value of the angle.

47. Second Method.—The vernier is set at zero and the angle turned 11 times, the first, sixth and eleventh being read and recorded. The first is subtracted from the sixth and the sixth from eleventh and each resultant divided by five to get the value of the angle to be observed. A random setting may be made and read and the fifth and tenth angles read and the resultant divided by five. Every alternate set is taken reading in the reverse direction on the vernier. A comparison between these two methods is afforded by the Hudson River tunnels of the Pennsylvania Railroad (A-18) where two independent corps were used to measure the eight angles of the river quadrilateral. Each corps read each angle about 300 times. The corps which used the first method obtained an average error in closure of 4.9 seconds and the corps using the second an average error of 1.4 seconds on the average of all angles turned. All angles were read by seven observers.

48. Third Method.—This was used with good results on the East river crossing of the first pair of tunnels from South Ferry, Manhattan, to Joralemon Street, Brooklyn, New York. It is described by Frederick C. Noble in *Trans. Am. Soc. C. E.*, vol. 75, pp. 68–111. In this method the angles were started at random near zero. Turnings were made accumulating from left to right until the sum became as nearly as possible 360 deg., or its multiple. Reversing the telescope and settings on the right hand target, the number of turnings was made from right to left until the sum was diminished to near the original reading. Both verniers were read at the beginning, at the middle, at intermediate points and at closing. In case an angle failed to close nearer than an average of 4 seconds to each turning the result was discarded and the angle was read again. When the third angle of any triangle of the system had been read, the angles were added, and if their sum varied from 180 deg. by more than an average of 5 seconds for each angle, the three angles were read again. The quadrilaterals were tested in like manner.

"In comparing the observed angles, it was noted that the direct reading of an angle was generally greater, by 2 or 3 seconds, than its value as found by taking the difference between two angles and that

at the end of an observation the closing reading was nearly always greater than the first. At this pointed to a small persistent error it was seen that it would have been a better program to measure each angle both directly and by its 360-deg. complement and to take the mean."

49. Adjustment of Error.—All the angles of the quadrilateral having been turned it will be found that the sum of the adopted means will not total exactly 360 deg. but will have an error of a few seconds above or below this. It is necessary, therefore, to adjust each angle separately by some standard method such as that given in "Theory and Practice of Surveying" by Johnston or in Wright's "Geodesy."

50. Computing Distance across the Waterway.—The distances across the waterway between opposite observation points are then computed, using each group of balanced or adjusted angles in turn. It will be found that discrepancies exist in the computed distances across the waterway according to whether the measured base lines are used with the large angles of the quadrilateral or whether the base line on one side of the river, calculated from that on the other is used.

51. Use Measured Base and Large Angles.—As the latter involves the use of the smaller angles, the sines of which have larger tabular differences per second of arc than the larger angles and as it seems reasonable to suppose that the measured length of the base is more accurate than the measurement of the angles turned, it is more satisfactory to calculate the distances across the water by using the measured base lengths and the large angles and if this is done and the work has been carried out with care along the lines indicated an agreement between the work of two separate parties to within five hundredths of a foot should be possible in a distance of 7,000 ft.

52. Night Work Is Best.—The observation of the angles is well done at night as the air is often clearer and more free from refraction than in the day time and the well-lit sighting points give clear and definite intersections.

53. Summary.—It will be clear from par. **44** to **52** that several general principles have to be observed in measuring the angles. These may be summarized as:

(*A*) Use several independent observers.

(*B*) Use a system of successive additions and subtractions of angular measurements and thus minimize inaccuracy of gradua-

tion in the instrument plate and variations due to faulty adjustments.

(*C*) Set the verniers at random.

54. The Transfer of Level.—It is obvious that the bench marks used on the two sides of the waterway must be referred to the same datum plane otherwise there will be an error of elevation when the tunnel driven from one shore meets that driven from the other.

55. Where a Level Sight Can Be Taken.—Where the waterway is not of width so great as to be beyond the limit of a sight with a level no particular difficulty is presented and it is merely necessary to start from some bench mark on one side of the waterway and take a sight across to the other side and thus establish a bench mark there. All operations will have to be done with unusual care and the run from the bench mark repeated until it is certain that consistent values have been obtained. Double turning points should be used and a re-run made whenever the two values for the height of instrument varies more than 0.004 ft. Fore sights and back sights should be kept as equal in length as possible and the rods equipped with spirit levels so that they may be held truly vertical. The rods should be carefully tested and compared and errors corrected.

56. Where a Level Sight Cannot Be Taken.—When the waterway is so wide that the direct use of an ordinary level would be

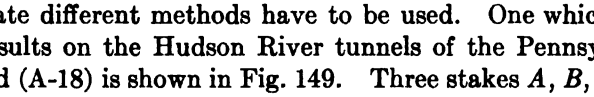


FIG. 149.—Method of transferring levels across a waterway which is too wide to permit direct level sights across it.

inaccurate different methods have to be used. One which gave good results on the Hudson River tunnels of the Pennsylvania Railroad (A-18) is shown in Fig. 149. Three stakes *A*, *B*, and *C*, were set on each side of the river about 200 ft. apart on a line at right angle to the direction of the waterway and carefully brought to the same elevation by an instrument set up near the middle stake, *B*. A level was then set up behind stake *A* and brought to an accurate horizontal plane by sighting on stakes *A* and *C*

thus establishing a base 400 ft. long normal to the earth's radius at the mid point B. As sights were taken simultaneously to the opposite points B and the results averaged no correction was necessary for earth curvature or refraction. These readings were repeated on different days and by different corps.

57. Transfer by Tide Gauges.—In cases where the waterway is not obstructed by islands or by the confluence of other streams, the transfer may be done also by tide gauges set on opposite sides of the waterway. Simultaneous readings of the gauges repeated often enough will give a means of establishing points of the same elevation on both sides of the waterway.

58. Example.—In the case of the Hudson River tunnels of the Pennsylvania Railroad (A-18), readings were taken over a period of 8 hr. for 31 consecutive days. The readings were taken at intervals of 2 min. at slack water and every 5 min. during the rest of the period. The mean difference of elevation between the benches as obtained from high and low water and intermediate readings were used to average with the results obtained by the instrumental method described in par. **56.** It may be of interest to record the values obtained as a basis of comparison with other work.

TABLE XL.—HUDSON RIVER, NEW YORK. RELATIVE ELEVATIONS FOR A BENCH MARK OBTAINED BY TIDE GAUGES AND BY LEVELING ACROSS THE RIVER

METHOD	ELEVATION OF BENCH MARK	
Tide gauge at high water	303.656	average of set of readings
Tide gauge at low water	303.752	average of set of readings
Tide gauge during tide run	303.669	average of set of readings
Mean of tide gauge results	303.692	
By leveling, 1st line of sight (Corps 5)	303.711	average of set of readings
" " 2nd " " " (Corps 5)	303.717	" " " " "
" " 3rd " " " (Corps 1)	303.618	" " " " "
" " 4th " " " (Corps 1)	303.581	" " " " "
" " 5th " " " (Corps 1)	303.608	" " " " "
" " 6th " " " (Corps 3)	303.789	" " " " "
" " 7th " " "(Corps 1 & 3)	303.666	" " " " "
Mean	303.670	
Adopted value	303.681	

(D) TRANSFER OF THE WORKING LINES AND LEVELS TO THE TUNNEL

(A) Line

59. Shafts.—Most tunnel work of the kind dealt with in this book is conducted from shafts. These shafts may be on the line of the tunnel or offset from the tunnel and connected by a cross heading. The center line and level bench mark having been located on the surface and the shaft sunk it becomes necessary to transfer the line and level as laid out on the surface to the bottom of the shaft and thence within the tunnel in order that the proper guidance for construction may be given.

60. Method of Transfer, Shaft on Center Line of Tunnel.—It is usual to transfer the center line from the surface to the bottom

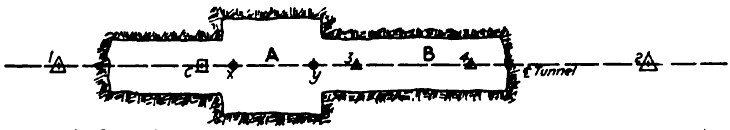


Fig. 150.—Plan of method of transferring the center line of a tunnel from the surface to the tunnel when the shaft is on the line of the tunnel.

of the shaft by means of fine steel wires supporting heavy weights. The general method is as follows in the simple case of the shaft being located on the center line of the tunnel (Fig. 150). We have, it may be supposed, a shaft *A* situated on the center line 1-2 of a tunnel *B*. The center line has been laid out on the surface and marked with monuments 1 and 2. If a transit is set

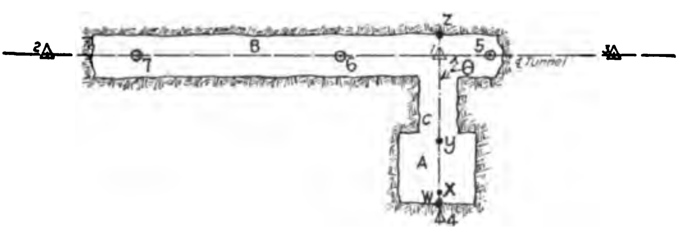


Fig. 151.—Plan of method of transferring the center line of a tunnel from the surface to the tunnel when the shaft is not on the line of the tunnel.

over monument 1 and sighted on monument 2 it will mark the center line. If we take two wires *x* and *y* each supporting a heavy weight and let them hang down the shaft they may be brought into line with 1 and 2 and if an instrument is set up in the tunnel,

say at C, and brought into line with x-y then this instrument will be also on the line 1-2 and can be used to establish points 3 and 4 in the tunnel which will be on the desired center line 1-2.

61. Shaft off the Center Line of the Tunnel.—The next most usual case is where the shaft is not directly over the tunnel but offset to one side as shown in Fig. 151. Here A is the shaft, B the tunnel and C the cross heading connecting the shaft and the

Fig. 152.—A leaden wing weight used to transfer the center line of a tunnel from the surface to the tunnel. These weights are hung down the shaft supported on a thin steel piano wire. The weight hangs in a pail of water, oil or molasses to prevent and check oscillation.

tunnel. The center line of the tunnel 1-2-3 has been laid out on the surface, the shaft has been sunk and the cross drift driven and a heading started along the approximate line of the tunnel. On the surface the angle θ is turned in series to a point 4 and the wires, x, y, set from point 4. Below ground, two points, as Z and W, would be set first. This is done by transit readings lined in on the wires at the same time that the wires are set on the

surface. A point in the tunnel directly below point 1, on the surface is established by measuring from the wire y and the angle θ then turned in the tunnel from the points W and Z thus

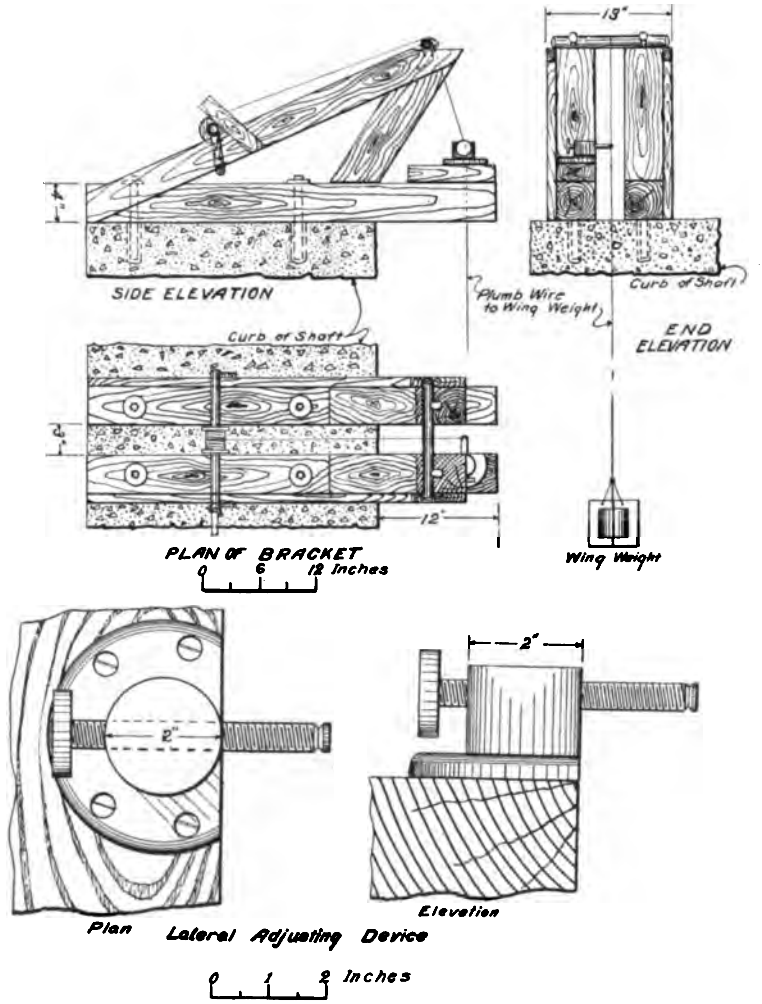


FIG. 153.—Details of reel with lateral adjustment for bringing into final position the wires, used to transfer the center line down the shaft.

enabling points on the center line as 5, 6 and 7 to be established in the tunnel.

62. Plumbing Wires.—The plumbing wires may be "No. 5" steel piano or spring wire, 0.018 in. diameter. They are kept

wound on a spool and when unwound kept under some tension, otherwise they will kink. New wire will be needed after every second or third use.

63. Weights.—The weights should weigh not less than 20 lb. and preferably from 30 to 35 lb. They may be of lead so that they are as small as possible. The proper form is the winged weight which is in the shape of a cross (see Fig. 152). The weights are hung in pails of water, oil or molasses. This is to prevent oscillation and to check it quickly if it occurs.

64. Reels.—The reels over which the wires are hung must be provided with a slow lateral adjustment so that the wires may be brought into perfect alignment. For this purpose they have a screw attached to the drum or cylinder over which the wire is hung. By turning the screw a lateral movement is given to the wire. Figure 153 shows one form of adjusting reel which has been found good. Tension is put on the wire by gradual application of the weight while this is in the pail of liquid; applying it otherwise will break the wire.

65. General Procedure.—Suppose for simplicity, that the shaft is placed over the center line of the tunnel. This line has been established on the surface. A transit is set up on a monument on the center line within reasonably close distance of the shaft, say from 10 to 50 ft. The instrument is sighted on the foresight and the wires lined in. The wires are suspended so that they are clear of the shaft by about a foot and careful inspection should be made to see that the wires are not touched by any object, such as projecting timbers. While the observer on the surface is sighting on the foresight and lining in the wires, another observer with another instrument is set up in the tunnel below as near as he can get within focus to the rear wire so that the near wire is out of focus when the transit is sighted on the far wire. When the observer on the surface has the wires lined in he signals to the observer below. This observer has an instrument with an orienting head. He shifts his instrument on the head until it is exactly on line with the two wires and then sights ahead on two or three vernier scales as far apart as the length of the tunnel already built will permit. These scales are made of brass and can be read by vernier to one-thousandth of a foot.

66. Operations Repeated.—This operation is repeated many times, a record being kept of the vernier reading at each repeti-

tion. Readings are taken with the telescope reversed, with the operator changed, with the upper instrument taken below and the lower to the surface, with the pails in which the weights are submerged turned around, with the wires shifted and then reset and in fact with everything possible done to eliminate all possible source of error.

67. Adopted Line.—After all this is done the verniers are set on the computed mean of the consistent readings and this is adopted as the working line below ground.

68. Stationing.—The stationing is transferred below by measuring from the monument on which the surface transit is set up, the stationing of which is known, to the nearest wire. This gives the station of the wire. By measuring from this wire at the bottom of the shaft to a plug or monument in the tunnel a reference point for the stationing of the tunnel is established.

69. Two Parallel Tunnels.—In shield driven work it is a common case to have two tunnels driven on parallel lines. It has been found convenient to set out the center line of the other tunnel from the center line of the first by means of a large "beam compass" set to the required distance between the two center lines. By this means it is certain that the two center lines are parallel. Whatever error there may be in the beam compass it is the same and true parallism is achieved, rather than minutely accurate distance apart of the two center lines. The beam is made of lumber, say, 12 in. by 2 in. and about 2 ft. longer than the required distance apart of the two center lines. Copper tacks are placed in the beam near its lower edge at the required distance apart and the distance marked on the tacks with fine punch marks, using a standardized tape (see Fig. 154). Monuments are established in the floor of the tunnel opposite cross openings between the two tunnels.

70. Method of Use of Beam Compass.—The beam is set up at right angles to the center line and levelled in accurately. The punch mark at one end is sighted in by transit so that it is directly over one of the monuments in the tunnel whose center line has been established. A monument plug has been set previously by approximate measurement in the floor of the other tunnel, a scale is set on this monument and the position of the second copper tack read by transit reading the scale. This observation is repeated by several operators until a set of consistent readings has been obtained. The mean of the scale readings is then taken

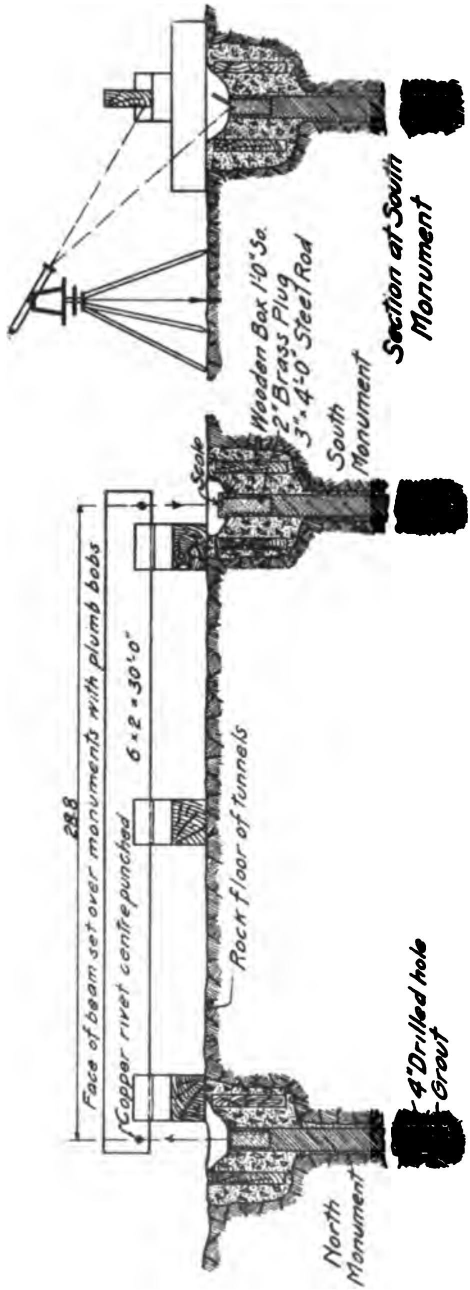


FIG. 154.—Method of using a "beam compass" to set the center line of one tunnel truly parallel with that of another.

as the adopted measurement and the mark on the monument marked by a punch mark. The operation is repeated for the other monument and then the line of the second tunnel is parallel to the first.

71. Method of Transfer by Transit Sights.—In place of wires used for transferring the line from the surface to the tunnel, transits have been used. These instruments are made so that the telescope can be used when pointing vertically downward. This is achieved by mounting the telescope on an overhanging support so that, when vertical, the telescope clears the horizontal limb and the leveling plates, or the instrument can be made with the telescope mounted in the ordinary way but having a slot

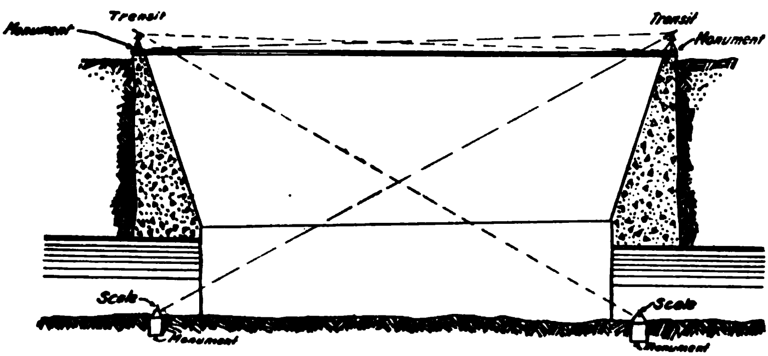


FIG. 155.—Method of transferring line from surface to tunnel where the shaft is on the line of the tunnel and large enough to enable the tunnel monument to be visible from the top of the shaft on the opposite side.

cut in the horizontal plates so that it may be swung to a vertical position. These instruments should afford a useful check on the accuracy of the work done with the wires. In very deep shafts to be perfectly sure that the wires are not touching some obstruction and to check the oscillations are quite difficult matters. If the shaft is very large in plan it may be possible to transfer the line by using ordinary transits, using two transits simultaneously and transferring the line diagonally (see Fig. 155).

72. Work Done at Night.—As in most of this survey work, the transfer of line from the surface to the tunnel is best done at night, the sights being lit by electric light boxes placed behind them.

73. Trial Run.—It is well to make a trial run in the day time, however, so as to have the advantage of day light to set the wire reels to closely approximate position, to see that the wires hang free and in general to test out all the methods and appliances. Then the party goes out at night to make the real observations certain that everything will go well. When the chief of the party is fussed and worried about how everything is going to turn out his anxiety, worry and nervousness will be communicated to every man in the party. Good work cannot be done under such conditions.

74. Alignment by Bore-holes.—Where the tunnel is long and the base distance between the two wires in the shaft is comparatively short, as generally it is, a longer baseline for the projection of the center line may be had by putting down bore holes on the line of the tunnel and by dropping wires down these holes. The positions of the borings are determined by sighting on the foresight. Borings of a good big diameter should be made. Ten-inch casings down to rock and 8-in. borings through rock are none too large, as the holes may not be quite plumb and it is essential that the wires shall hang free.

75. Method of Procedure.—The borings having been made, wires are supported above the holes and lowered down the bores with plumb-bobs at their lower ends. The wires are lined in by observations to the foresight on the surface. Permanent monuments are then established in the floor or roof of the tunnel in front of the wires. These monuments are brass plugs set in concrete and will vary in detail according to local conditions. The monuments having been set, the wires are again lowered down the bore holes and the heavy wing weights attached to their lower ends. As before, the weights are immersed in pails of water, oil or molasses. The wires are carried on adjusting reels as for the shaft work and brought to exact alignment with the foresight by an observer on the surface. Simultaneously two transits in the heading near each monument are set in line with the two wires. When satisfactory sets of scale readings have been taken on several different occasions with different observers and different instruments the mean scale reading is marked on each monument plug by small drill holes. It is essential that the wires do not touch the sides of the bore holes. A powerful electric light can be used from the top and from the bottom to see that the wires are free. If the bore hole is cased with pipe for its whole

length an electrical device may be used to tell whether the wire is touching the casing.

(B) Transfer of Level

76. Method of Procedure.—A bench mark is established near the top of the shaft. A standardized tape supported several feet above the surface is hung down the shaft and the standard tension obtained by hanging a weight fastened at the lower end. At the surface a level reading is taken from the bench mark to the tape. Simultaneously at the bottom a reading is taken from a level to the tape. The difference between the two readings, corrected to the temperature at which the tape is standard is the difference in level between the two instruments. Since the elevation of the line of collimation of the upper instrument is known, that of the lower is known also. The lower instrumentmen observe the elevation of the lower bench mark. The operation is repeated by different observers until a consistent value is obtained for the lower bench mark.

(*E*) CARRYING FORWARD THE LINE AND LEVEL IN THE TUNNEL

77. Effect of Character of Ground.—The process of carrying forward the line and level is simple or complicated depending on the kind of ground which the tunnel penetrates. If the tunnel is through firm soil and is under normal air pressure, it is a comparatively simple matter to carry forward the working lines and levels. If compressed air is used a complication is at once added by the presence of the bulkhead wall, as the transfer of all lines and levels has to be made through the air locks. If the ground through which the tunnel is built is unstable mud, the entire tunnel, while under construction, will be in a state of movement, both vertical and horizontal, so that marks established in the tunnel will not be stable and cannot be used as guidance for the construction without constant renewal by carrying forward lines and levels established in the portion of the tunnel which is in stable ground.

(A) Tunnels under Normal Air Pressure

78. Guidance of Shield.—Virtually, the shield is continually traveling forward and the position of the shield determines the

position of the tunnel which is built within the shield. It is consequently important to be able to "check" the shield before and after each shove so that precise knowledge of its relationship to the desired line may be had so that if it is deviating from the line immediate steps may be taken to stop and correct such deviation. The same is true of grade.

79. Line Carried Close to Working Face.—It will be the duty of the alignment engineer, therefore, to see that his line is kept well up to the working face so that it may be at all times read y available for the inspectors and the shield foremen. This working line is projected ahead from the precise line and at least three points on the precise line should be used to project forward the working line.

80. Laying out Curves.—To lay out a curve, the tangent offsets from the first tangent are computed for each 10-ft. station until a point, perhaps 50 ft. beyond the intersection is reached. Enough distance beyond the intersection point is allowed to turn the intersection angle for temporary use.

81. Points on Curves.—On a curve it is customary to place two points, one a direct foresight point established by repeated readings on the scale, the other a right angle offset point on the curve itself.

82. Permanent Foresight on Curve.—When the tunnel is about 250 ft. ahead of the intersection a permanent foresight is set. This is done usually by setting a scale approximately on the curve at a known distance from the intersection and then turning a series of angles to a point set roughly to line and correcting any error by measuring the correction on the scale by a corrected tangent offset. It is possible often to check the scale also by setting a point at the desired station on the first tangent prolonged and then measuring the entire tangent offset. If the intersection point does not fall within the confines of the tunnel the curve is laid out in like manner, using one or more chords and intersections.

83. Distance between Monuments.—The distant apart of the precise line monuments will vary with the degree of clearness in the tunnel air. It will be found usual that they cannot be much further than 300 ft. apart, and 200 ft. is a common interval. In order to obtain the accuracy derived from repetition it is the custom to use alignment scales arranged as shown in Fig. 156. On these scales repeated readings can be taken and the adopted

line set as a mean of the vernier readings. These scales not only serve to give an accurate point but preserve a record in case of movement and give a check on individual runs.

84. Work Not to Interfere with Construction.—The survey work must be done without interfering with the progress of construction, which in tunnels is usually carried out continuously the by night as well as by day. Consequently it is found best to set

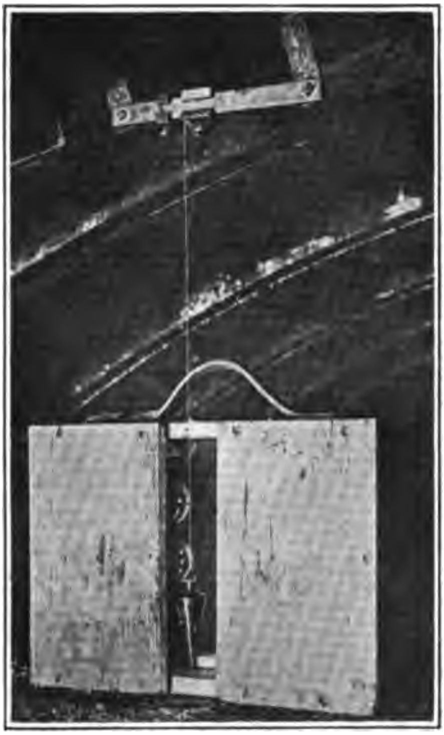


FIG. 156.—A vernier "alignment bar" in a cast-iron lined tunnel, showing the plumb-line hanging from it and a light box of the second or shrouded type (see text, Par. 87) behind the plumb-line. Pennsylvania Railroad Hudson River Tunnels (A-18). (Courtesy of *Pennsylvania Railroad*).

instruments on special tables or brackets permanently attached to the lining of the tunnel for this purpose. By the use of these tables the tripods of the instruments are not needed and the instruments can be set up on three-legged stands or trivets standing on the tables, which are placed so that the man using the instrument is out of the way of the construction and tunnel

transportation work. The trivets must be heavy castings with wide spread of feet. No spidery-legged trivet is of any use.

85. Platforms on Center Line of Tunnel.—When the tunnel is of 20 ft. diameter or over it is possible to use instrument tables on the center line of the tunnel above the traffic, a separate platform being used by the observer.

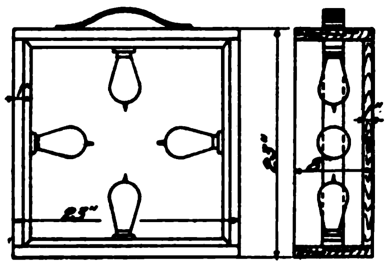


Fig. 157.—Tunnel light-box with electric lights screened by tracing cloth.

86. Sighting.—It is usual and best to take sights on a suspended plumb line. The hairs are conveniently set to intersect at an angle of 60 deg. with a horizontal hair. There must be no vertical hair in the tunnel transit.

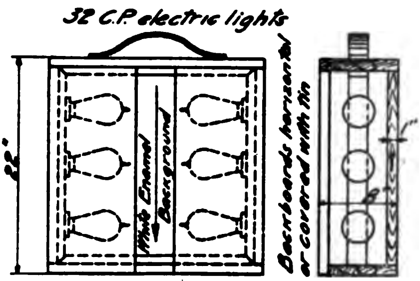


Fig. 158.—Tunnel light-box with lights shrouded from direct sight.

87. Lighting.—The plumb-bob line has to be lit so that it stands out clear and black against a white background. For this purpose a "light box" is used. One form consists of an open box with the face covered with tracing cloth and having one or more 16-candle power electric lights behind the tracing cloth (see Fig. 157). This type has certain objections. Where the air is thick and several lamps have to be used there is too much glare. Another type which overcomes this glare is shown in Fig. 158.

This type contains four or six 16-candle power lamps placed at the side of the box and the lamps themselves concealed by front boards. The inside of the box is painted dull white and acts as a background against which the plumb-bob line is outlined through the opening between the cover boards. Figure 156 shows one of these light boxes set up below a vernier scale alignment bar.

88. Levels.—The levels are carried forward from the original bench mark as established from the surface. A fresh run should be made from the original bench mark once a week. The turning points should be about 200 ft. apart. Turning points may be some projection of the lining or a bolt head or some special turning point made for the purpose, for example an inverted railroad spike projecting from a block of concerte set in the side of the tunnel. An ordinary Wye level is the most convenient type.

(B) Tunnels in Compressed Air in Stable Ground

89. Air Locks.—In tunnels driven under compressed air through stable ground the only complication added to the case of the tunnel in normal air is the air lock. When the tunnel is large enough there will be three air locks through each bulkhead wall. Two of these will be on the working floor level and will be used for the passage of men and materials. The third lock will be the emergency lock, set as high in the bulkhead as possible, and kept open to the compressed air chamber at all times to afford a means of escape to the shield gang should the face be lost. Sometimes the emergency lock is used to carry the lines and levels through the bulkhead. This is not good as it deprives the shield gang of its safety exit, but using the other locks would interfere with the work of construction. In Chap. VII it is suggested that when the cross-section of the tunnel is large enough a special engineer's lock should be provided.

90. Position of Lock.—Whatever lock is used, its position in the bulkhead wall should be laid out with reference to the carrying forward of the working lines through it without having to make a special offset in the line to get through the lock. It will be found better not to place the axis of the lock directly coincident with the working line but a little to the one side, thus giving more room to pass the transit when set up in the lock.

91. Transferring Line through Lock.—The method of setting an instrument in the lock is shown in Fig. 159. The line point may

be marked by a brass plug set in a drill hole in the bottom of the lock. A plumb-bob is hung above, and just avoiding, the plug and readings taken on a small scale temporarily set for the purpose at each run of the line. This gives no permanent record, however, and it is better to set in the crown or floor of the lock

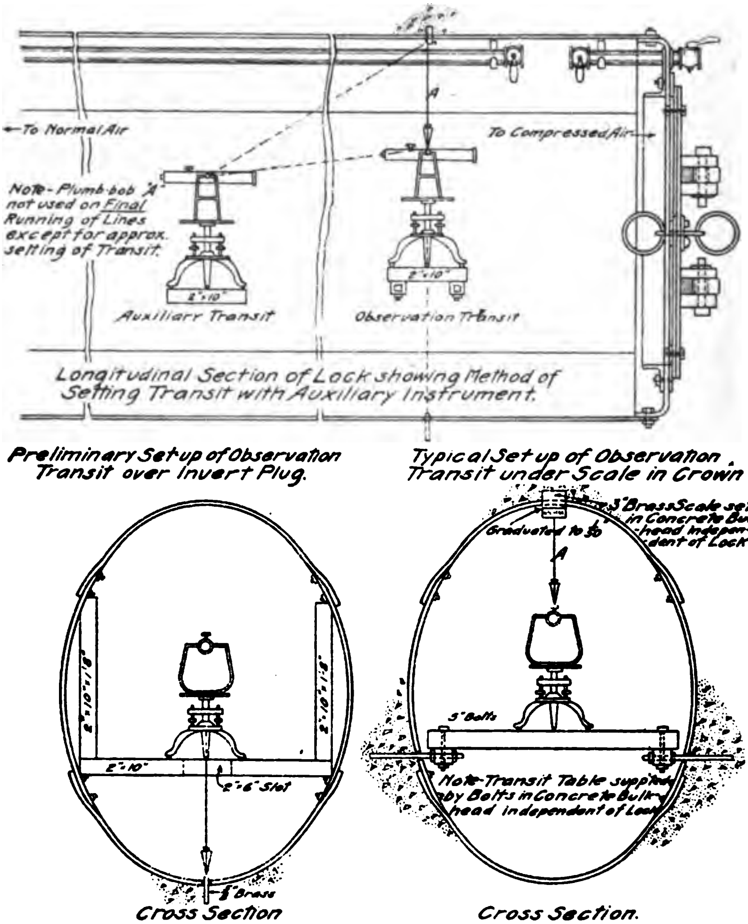


FIG. 159.—Methods of setting transit in air-lock.

a brass alignment scale 1 or 2 in. long and divided to $\frac{1}{50}$ in., on which readings may be interpolated to $\frac{1}{100}$ in. Sights can be taken on a suspended plumb-bob outlined by a light box set up at the rear of the plug. If the material lock is used

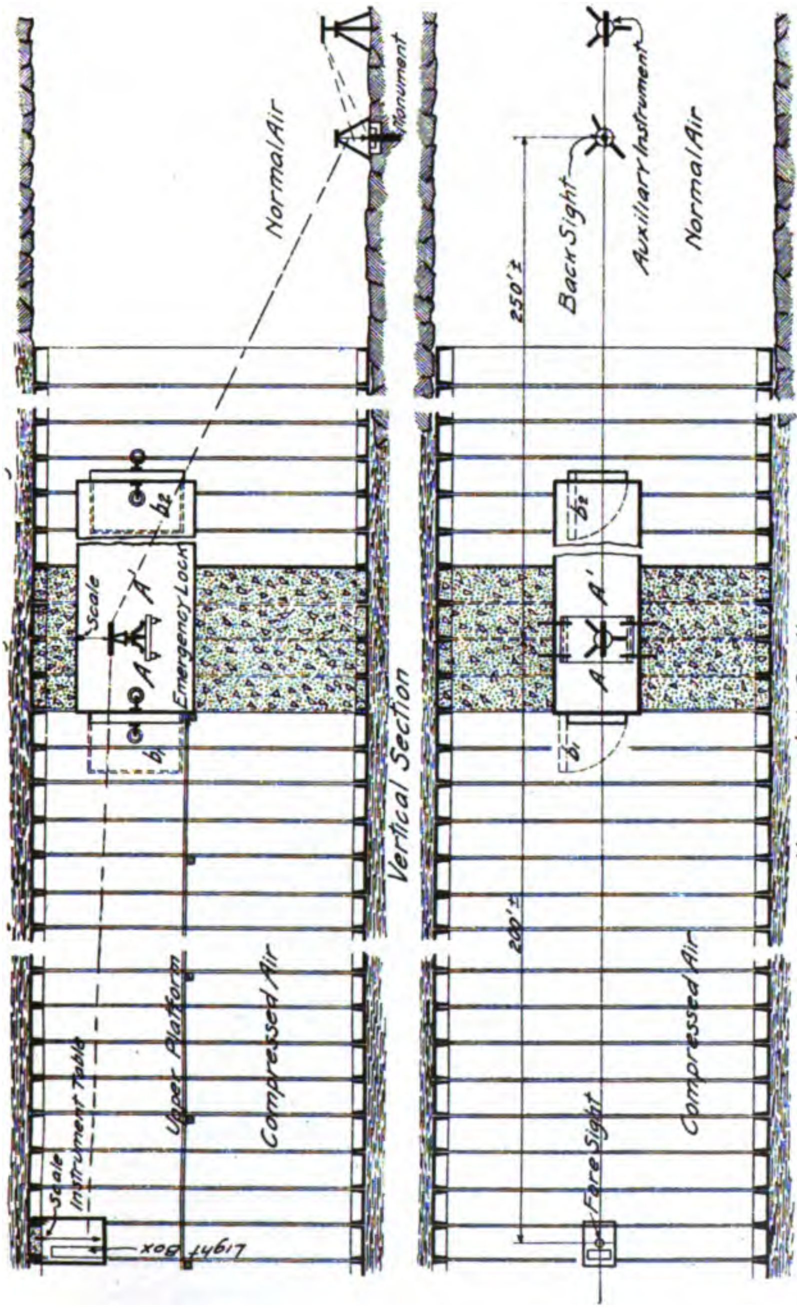


FIG. 160.—Method of transferring lines through air locks.

for the line work the vernier must be set close to the roof to avoid damage to the scale.

92. Method of Transfer to Lock.—To transfer the monument line to the lock the transit is set up over the monument near the lock and a plumb-bob suspended over the rear monument and both transit and back sight lined in with auxiliary instruments. A back sight is then taken and the line transferred by transiting the telescope to the plumb line suspended from the scale in the lock. Several series of readings with reversal of telescope should be taken. If the air is clear a check can be made by setting up over the rear monument, sighting on the monument nearest the lock and reading the scale in the lock.

93. Method of Transfer through the Lock.—The method of transferring the line through the lock is shown in Fig. 160. The back sight is set up over the monument nearest the lock by an auxiliary transit and an observer stationed in position A in the lock with the door b_2 open. The instrument being set on the back sight the observer locks through and the door b_1 opened. The observer takes up the position A^1, the foresight plumb line is moved to position, a reading taken on the scale and recorded. This process is repeated and after several readings the positions of the instrument and back sight are carefully rechecked. When lack of clearance in the lock does not permit the observer to pass the instrument two observers are used, one at A and the other at A^1. The one at A takes the back sight and the one at A^1 sets the fore sight.

94. Method in High Air Pressure.—When the air pressure is high a method can be used which avoids the necessity of a man locking through with the instrument. The observer A takes the back sight and then leaves the lock by the door b_2. The instrument is then locked through. The observer A^1 enters by the door b_1 and sets the fore sight, after which he leaves the lock and the instrument is locked out to normal air. Time is saved by this method.

95. Transferring Levels through Lock.—To transfer the levels through the lock a turning point is established on a point in the air lock. The instrument is then taken to the first level table inside the air chamber and a back sight taken on the point in the lock. No set up in the lock is necessary.

96. Stationing in Tunnel during Construction, Rapid Method.—A method of stationing in the tunnel which permits rapid work

but is not as accurate as a second method, which will be described, is carried out as follows: Intermediate points are set at rather less distance apart than the length of the tape, say at 98 ft. more or less for a 100-ft. tape. These points may consist of horse-shoe nails drilled for a bob string and driven in a block of wood wedged in the lining. The tape is supported at the ends only under a standard tension and several readings taken and recorded. The mean difference is corrected for sag, temperature, gradient and tape constant. This method is good for a first approximation or check.

97. Stationing, Accurate Method.—The second method uses the same sort of intermediate points but leveled tape supports are used every 20 ft. The tension is obtained by spring balance or weight. Corrections are made for slope, temperature and tape

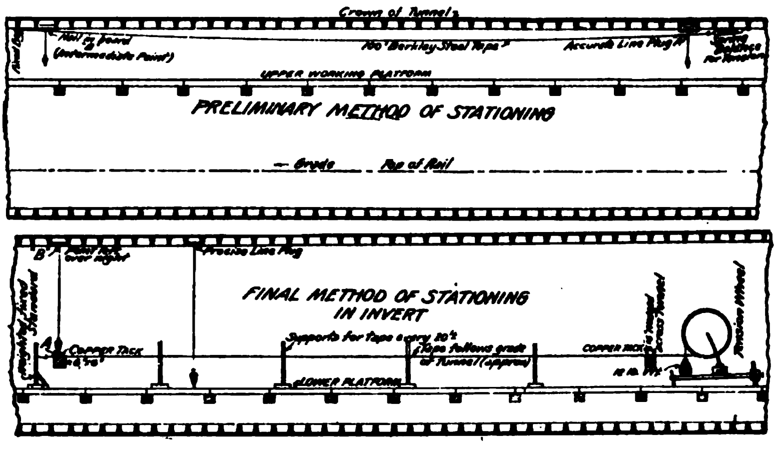


FIG. 161.—Two methods of "stationing" in a tunnel. The upper is a rapid method giving a good approximation as the work of tunnel driving proceeds. The lower is a slower but more accurate method for use after the driving period is over.

constant. This method takes longer time but gives better results. It should be used for final stationing. The methods are shown in Fig. 161.

(C) Tunnels in Unstable Material

98. Conditions in Unstable Ground.—Some shield driven tunnels have been built through unstable mud. In this material the troubles of the alignment corps are much intensified, because the

tunnel itself will not be in a fixed position and shape. It will rise and fall, will move laterally and will change shape. Any line mark or bench mark, therefore, which is established in the tunnel will not be stable and in order to have true lines and grades at the working face it is necessary to re-run the line and levels from monuments and bench marks established in a stable part of the tunnel. The frequency with which the lines and levels must be re-run will depend on the rate of advance of the shield and on the magnitude of the movement and distortion, but it will be necessary to make the run at monthly intervals or less, as the progress of the shield through such material is usually great. The methods used will be as described above. The alignment scales will have to be 10 in. or so in length so that the movement of the tunnel will not carry the scale off the line. When the line is re-run a record must be taken of the reading on each scale so that the movement of the tunnel is recorded. The same applies to the elevations.

99. Check through Cross Pipes.—A useful method of making a check on the accuracy of the line and level as run in each separate tunnel, is afforded when two tunnels are run parallel to each other, by driving a pipe or a pair of pipes some distance from each other from the side of one tunnel to and into the side of the other. Through these pipes the distance between the center line in one tunnel from that in the other may be measured and a check on the accuracy of the work is thus obtained. It is a cheap and easy thing to put in these pipes and even in the softest mud no difficulty exists. It may then be necessary to tap bolt a stuffing box on the inside of the tunnel lining in which the pipe can slide, and thus exclude mud and water from entering the tunnel. In general a 6-in. pipe will do. The pipe should be driven square to the center line, but above all else it must be level so that the line and level measurements may be taken directly through it without computation. This method of obtaining a check is analogous to that obtained by sinking a vertical boring from the surface through which to drop a plumb line.

(F) CHECKING THE POSITION OF TUNNEL AND SHIELD

100. Work of Alignment Corps.—In any shield driven tunnel the work of the alignment corps will be divided into two main parts, namely:

(*A*) Running the precise lines and levels through the tunnel so that a means is afforded of knowing whether the shield is traveling on the pre-determined lines and gradients.

(*B*) "Checking" or testing the position of the shield in order to see whether it is traveling in the direction desired and at the same time observing the general shape and condition of the lining erected.

The methods in general use for the first part of the alignment work have been described and some account of the second part will be attempted.

101. Conditions Met.—Ideal conditions for keeping true line and grade may be imagined. The material passed through should be stable and self supporting and the segments of which the lining is built up should be absolutely true to shape. In such a case, if the first ring of the lining were erected in its true position and perfectly square to the desired line and the shield shoved perfectly square to this ring then the shield would travel on the desired line and grade and by constant repetition of this condition a perfectly aligned and graded tunnel would result. In practice such conditions are not, and will not be, met. The segments are never absolutely true and even if they were, it is impossible, even with the greatest care, to prevent small quantities of dirt getting between the joints, especially at the bottom. The shield rarely can be driven perfectly normal to the true center line, because the method of control, which is by the jacks, is not delicate enough to permit this to be done. The material passed through is generally far from ideal from the view point of keeping true to line and grade. Rock, sand, gravel, clay and mud all have their particular peculiarities. As a general statement, it may be said, that no shield driven tunnel is built exactly to line and grade. The actual work will consist of a series of undulations around the line and gradient laid down. These deviations cannot be allowed to exceed the small limits imposed by the design. For motives of economy the cross-section of the tunnel will be kept down to the smallest limit and deviations from line and grade consequently must be small. The smaller and gentler the undulations are the better.

102. The Secret of Success.—If the shield is high, for example, do not get scared and try to jam it down in the shortest possible length. To do so will invariably lead to its getting too low in a short distance and will make it difficult to establish a final gradi-

ent that is satisfactory. The secret of success is frequent and careful checking so that any tendency to deviate is known as soon as it begins to occur and proper steps taken to remedy the fault. Accuracy is absolutely essential. All measurements should be verified by an independent observer. Cases have been known where a shield check indicated the shield to be too high so that steps were taken to bring it down, whereas in reality it was low. This could have been avoided by proper recheck. The result of bringing down the shield which was already too low was a horrible kink in the grade after months of careful and accurate work. Here, if anywhere, is a place where no visual check on the accuracy of survey work is possible. The whole thing depends on the men and on their instruments and no pains and care should be spared in seeing that their work is reliable. A tunnel built with bad lines and grades is an abomination and everything should be done to see that the deviations are kept within the smallest possible limits. The seriousness of the matter will be understood when it is realized that, if the deviations exceed the permissible limits set by the design, a part of the tunnel may have to be rebuilt, and this will be at any rate expensive, and possibly a dangerous matter.

103. Position of Tunnel and Shield.—The building of a shield driven tunnel is peculiar in that the permanent position of all parts of the structure, (aside from the generally slight subsequent movements) is determined before it is built, by the position of the work already built and by the position of the shield. The position of any part of the work already built is the result of the position of previous work. The position of the shield after a shove is a matter which cannot be more than roughly predicted or governed under the conditions by which it is controlled. For this reason every shove is virtually a new experiment.

104. Factors Determining Position.—The principal factors which determine the position of a ring with regard to line and grade are:

1. The position of the preceding ring. If the preceding ring is 3 in. off line the next ring will be about 3 in. off line too.

2. The direction of the face of the preceding ring. If the face of the ring deviates from a plane at right angles to the axis on which it should be traveling it is said to have a lead. Thus, if it is said that a ring has a lead of 2 in. on the right, this means that if a line at right angles to the center line is projected across the

tunnel it will be found that the right hand edge of the ring is 2 in. ahead of the left. The next ring when built against it will be thrown to the left. If the lead is on the top the next ring will be thrown downward and if on the bottom, upward. The lead of the lining can be changed by the use of taper rings or by taper packings in the circumferential joints between adjacent straight rings.

3. The "play" or clearance between the lining and the shield. If the shield is square to the line of the tunnel and the tail bears against the outside of the lining at the bottom, the next ring will be about the same height above grade. If, on the other hand, there is room between the shield and the lining at the bottom, the lining, taking advantage of whatever play there is in the bolt holes or other connections between ring and ring, will drop by its own weight to a slightly lower position. If at the end of the shove the shield is bearing against the iron on one side and itself has a lead on the same side, the next ring will be forced over slightly to the opposite side. The size of the play can be changed, but only gradually, by changing the leads on the shield. When the shield is not bearing on the lining at any point and it is desired to have it do so, large leads may be used on the shield until it begins to bear, after which the lead on the shield should be reduced. To gain time, wedges may be driven between the shield and the lining. This has to be done with great care and should be done only in emergencies. It is inadvisable to have the shield bear on the top of the lining for any longer than can be helped as it makes the erection of the lining difficult.

4. The lead of the shield from the iron. For example, if the shield has a lead of 2 in. on the right and at the same time is bearing against the lining at that side, the ring being built will be thrown toward the left. In soft mud the shield leads are easily controlled and may be entirely changed in the course of a single shove. In sand or gravel sudden changes of lead should be avoided as they may cause the tail of the shield to split. A lead of the shield cannot affect the tunnel, however, until the shield is actually bearing against the lining. Then it can throw the ring that is being erected over by taking advantage of the play in the lining connections.

105. Meaning of Shield Check.—It will be seen from the foregoing that in order to enable the engineer to understand fully the conditions at the face and, so understanding, to issue the proper

orders for the guidance of the shield and the building of the tunnel, he must have the following, which comprises the shield check:

(*A*) The position of the last ring completed with regard to line and grade.

(*B*) Its leads, both lateral and vertical.

(*C*) The changes in (*A*) and (*B*) since the previous check.

(*D*) The actual leads of the shield.

(*E*) The play of the lining in the tail of the shield at each side and at top and bottom.

(*F*) In soft mud, since the shield is guided to some extent by the volume of ground taken in through the shield and the position of the opening through which it is taken in, it is necessary to know the volume of mud taken in and the point at which this was done.

106. Method of Checking.—The check, which takes a party of four men to do, is made on the shield and on the last ring on which the shield has been shoved. The reason why this ring is used is so that true diameters and radial measurements may be obtained. The bolting up on the leading ring before a shove has been taken on it is liable to be unfinished and, therefore, a check on this ring is not desirable.

107. Deviation from Line.—To obtain the deviation from line the transit is set up under the leading transit point and two or more sets of reversed readings taken on the forward circumferential flange at the top of the ring next to the shield. The mean of the readings is marked with a pencil or a chisel. This point is marked on the near side of the far flange of the ring as shown in Fig. 162. The tape is stretched across the tunnel between the front flanges of the ring checked and swung to determine the horizontal axis *a*-*c* and the largest reading recorded as the horizontal diameter. A plumb-bob is hung from the line point just marked and the intersection *b* of the plumb line with the tape read and recorded. The difference of the two lengths *a*-*c* and *a*-*b*, gives the measurement *b*-*c*. These radial measurements should be read separately by holding the tape successively at the two sides and reading at the plumb line as a check. The readings are recorded in a note book specially ruled for the use of the shield

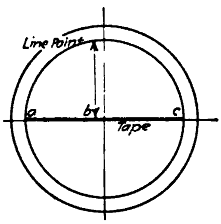


FIG. 162.—Method of obtaining the deviation of a tunnel from the correct line.

checking corps. One-half the difference of the radial measurements *a-b* and *b-c* will be the deviation of the tunnel from its proper center line. The direction of the deviation will be on the side of the longer radial reading.

108. Vertical Diameter.—The vertical diameter is taken by holding the zero of the tape on the top edge of the front circumferential flange at the bottom of the ring being checked and swinging the tape at the top against the same flange. The longest reading will be the vertical diameter. This is recorded in the note book in the place provided.

109. Diagonal Diameters.—The diagonal diameters are taken the same way as the vertical diameter, except that the tape is held so as to give diameters which are on lines inclined 45 deg. more or less to the vertical.

110. The Inclination.—The inclination, or vertical lead, of the lining is taken by lowering a plumb-bob from the top face of the front flange which is being checked to a point opposite the lower flange and then reading the distance from the plumb line to the lower face (see Fig. 163). The inclination of the shield is obtained by measuring from the face of the ring to the face of the shield. On a descending gradient, if the upper measurement *a* is greater than the lower *b*, the inclination of the shield is greater than that of the lining and the difference of the measurements is added to the inclination of the lining to obtain that of the shield. If the lower measurement *b* is the greater, the inclination of the shield is less than that of the lining and the difference of the two is subtracted from the inclination of the lining to obtain that of the shield. On an ascending gradient the reverse is true. These top and bottom measurements are recorded in their proper places in the note book as well as the resultant inclinations both of the shield and of the lining. The difference between the actual and that proper for the designed gradient are also recorded.

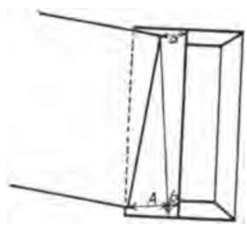


FIG. 163.—Method of measuring the "top lead" or "overhang" of the lining and of the shield.

111. The Lead of the Lining and Shield.—"Lead boards" are maintained on the sides of the tunnel at axis level and within 50 ft. of the face. These are pieces of board attached to the tunnel lining. On each board is a mark so placed that a line joining

the marks is at right angles to the true center line. Measurements are taken from the square marks on each board to the front edge of the lining ring being checked. These measurements are recorded in the note book. The difference between the two measurements is the lead of the lining. The lead is on the side of the longer measurement. The lead is also recorded in its proper place in the note book. The lead of the shield is obtained by measuring from the lining to the face of the shield. If the lead of the shield from the lining is on the same side as the lead of the lining from the square the two leads are added to get the actual lead of the shield. If on opposite sides, the difference is taken and subtracted from the lead of the lining. These shield measurements and consequent leads are recorded in their places in the note book. On curves the lead required on the outside of the curve must be computed.

112. Stationing.—As the station of the leading line point from which the right angle is turned to the points on the lead boards is known, the stationing of the points on the lead boards is known also and the average of the two measurements for lead added to this station will give the station of the ring which is being checked. The stationing of the leading line point and lead points are entered in the note book and also the station of the ring checked. The station of the cutting edge of the shield is obtained by adding a fixed dimension, depending on the shield, to the station of the ring checked.

113. Levels and Elevations.—Using a bench mark at least 200 ft. back from the shield for the starting point elevations are taken on the rings previously checked upon from the second tenth ring back from the shield up to and including the leading ring. After taking these readings a check should be made upon the bench to see that the instrument has not shifted nor error made in the first reading. This check back never should be omitted. The proper elevation for the leading ring is worked out from a table of grades previously prepared and the distance the invert of the tunnel above or below the designed elevation is entered in the note book. On vertical curves the computed offsets must be applied. The vertical diameter is added to the elevation of the invert and the variation of the soffit elevation from that designed is also recorded. Invert and soffit elevations together with a horizontal diameter are taken on every even tenth ring as soon after erection as possible, unless such ring is one on which

complete check has been made. These tenth ring records are for the purpose of subsequent surveys in order to know whether the lining is undergoing changes of elevation, shape or both.

114. Check Measurements.—On the second tenth ring behind the shield the elevations are taken as described together with a number of measurements by which subsequent changes of shape in the lining may be observed. The vertical and horizontal diameters should be taken, also the diagonal diameters at an angle of 45 deg. If these cannot be taken by reason of the trailing platform or other obstructions then some such chords and diagonal measurements which can be repeated at a later date should be taken. This is indicated in Fig. 164. There should be a standard way of making these measurements so that they are always made to the same points. If the lining is erected to break joints the points to which measurements are taken may not come always on cross joints. In such cases chisel marks should be cut in the lining at the points to which the measurements are taken so that subsequent measurements are made from the identical points.

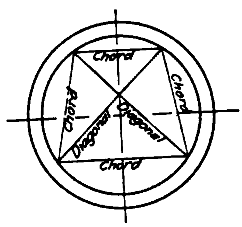


Fig. 164.—Check or record measurements of the shape of the tunnel lining.

115. Special Rings.—All special rings must be recorded. For example, taper rings with their direction, such as depressors, elevators, or side tapers; if side tapers, the side of the tunnel on which the taper is placed. If cast steel rings are used in places, these should be recorded, or rings tnrned over in special positions for cross passages or other purposes. If different weights or dimensions of segments are used this should be recorded. Everything should be entered in the note book which leads to a complete record of the lining.

116. Tests of Air.—In many compressed air tunnels it is made a practice to take each day a sample of the air in the working chamber and to analyze this sample for the contents of carbon dioxide (CO_2). The result of this test when made should be entered in the book.

117. Notes.—The notes taken should be recorded legibly and fully so that any one, beside the writer, may read and understand them. All computations should be worked out in the tunnel and checked by another man on the spot so that any discrepancy

may be discovered and checked at once. The notes should be signed by the note keeper and the checker.

118. Report Cards.—After the check is complete report cards are made out. These cards should show the following:

Tunnel
Date
Gradient
Curvature
Station of cutting edge of shield
Last completed ring number
Vertical diameter of last ring
Horizontal diameter of last ring
Station of front of last ring
Elevation of key
Elevation of invert
Deviation from line to-day
Deviation from line last report
Difference in line deviation
Deviation from level to-day
Deviation from level last report
Difference in level deviation
Inclination of lining, actual
Inclination of lining, required
Lead on lining
Lead on shield
Number of rings erected since last report
Lateral taper rings
Vertical taper rings
Other special rings
Second tenth ring behind shield, No
Second tenth ring behind shield, vertical diameter
Second tenth ring behind shield, horizontal diameter
Second tenth ring behind shield, top chord
Second tenth ring behind shield, bottom chord
Second tenth ring behind shield, right side chord
Second tenth ring behind shield, left side chord
Second tenth ring behind shield, right diagonal
Second tenth ring behind shield, left diagonal
Second tenth ring behind shield, elevation of key
Second tenth ring behind shield, elevation of invert
Air analysis at face CO_2, parts per 1,000
Air analysis at face, quality
Air temperature
Air pressure at first lock
Air pressure at second lock
Signature

Asst. Engineer.

119. Use of Report Cards.—The engineer in field charge uses these reports as a basis on which to frame his instructions for driving the tunnel until the next check.

120. Colored Cards.—It is found convenient, where there are several tunnels being driven simultaneously to distinguish between reports by assigning a different color to the card reports and forms for each tunnel.

121. Card of Instructions.—Based on the report of the shield check a card is made out for the shield foreman and tunnel inspector. This card is kept filed in a special box made for it which is hung in the tunnel near the shield at the telephone so that the foreman and the inspector can refer to it at any time. This card shows:

Deviation from line....................................
Deviation from level...................................
Lead on shield...
Lead on lining...
Inclination on shield..................................
Inclination on lining..................................
Vertical diameter of lining............................
Horizontal diameter of lining..........................
Play of lining in shield, right side...................
Play of lining in shield, left side....................
Play of lining in shield, top..........................
Play of lining in shield, bottom.......................

and a copy of the engineer's instructions as to what leads are to be used in shoving, what taper rings to use and any other necessary instructions.

122. Cards Made in Triplicate.—The report cards and the shield cards are made in triplicate, one copy for the chief engineer's office, one for the contractor and one for the resident engineer's own file.

123. Graphical Records.—It cannot be urged too strongly that the deviations from line and level as disclosed by the daily shield check and tunnel check be plotted graphically on cross section or profile paper so that a continuous picture of the line and gradient of the actual tunnel as compared with the designed line and gradient is at all times before the eye. The diagrams should be plotted at every check and not allowed to lag behind. They are of the greatest possible help to the engineer in his efforts to direct the shield properly and to keep the inevitable undulations of the tunnel along its pre-determined course as long and as slight as possible. A similar graphical record should be kept of the measurements on the second tenth rings behind the shield so that any marked change of shape or of elevation may be noted at once and proper steps taken to correct such changes or to prevent them from increasing.

124. Routine.—Everything should be laid out so that the operations of checking and recording the tunnel become a matter of well organized routine, making everything go like clock work and reducing special work to a minimum.

125. Anxious Period at Junction of Shields.—No one who has been through it can forget the period of anxiety which pervades the engineer's mind in the few days before his shields come to their meeting point. He cannot see where they are and he turns

over and over in his mind all his days and nights of work and wonders whether, hidden somewhere unsuspected, some obscure error will lead to a bad junction.

126. Special Work at Junction.—It is possible generally to take some steps which will allow any small irregularities to be ironed out before the shields come together. A small heading may be driven through from one shield to the other so that the line and level in one tunnel can be checked through with those in the other. If they do not agree exactly a new line and a new gradient which will bring the tunnels together without perceptible curve or kink are used for the closing portion.

127. In Soft Mud.—In some kinds of soft mud it is impossible to drive a heading. In such cases a pipe can be pushed or washed through when the shields are 50 ft. or so apart. The line and grade are checked through the pipe and if adjustments are needed they can be made.

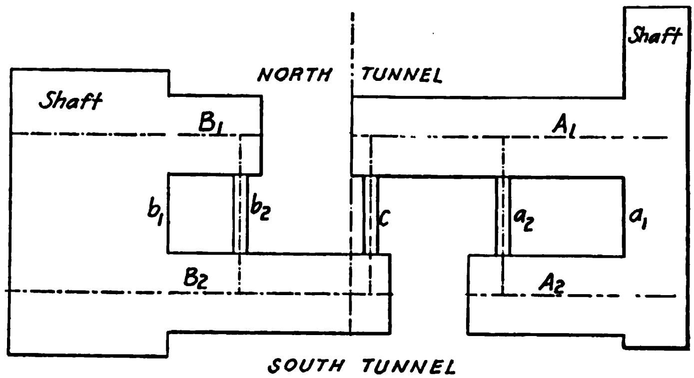


FIG. 165.—The "overlap check" of lines and levels previous to a junction.

128. The Overlap Check.—When the work comprises two tunnels lying side by side a satisfactory check can be obtained by driving one tunnel of the pair from one shaft until it overlaps the other tunnel of the pair driven from the other shaft. This is shown diagrammatically in Fig. 165. When the requisite overlap has been obtained a pipe may be driven through from one tunnel to the other and thus a satisfactory relationship between the lines and grades carried forward from one shaft and those from the other shaft established. It is clear from the figure that the lines and grades in the tunnels $A1$ and $A2$ agree while those in the tunnels $B1$ and $B2$ are the same, since they will have been

checked through at $a1$, $a2$ and $b1$, $b2$ respectively. The doubt is whether the A lines truly coincide with the B lines. By transferring the $B2$ line through the pipe c the effect is that the tunnel $A1$ is placed on the $B1$ line, and thus a perfect check is afforded. The same applies to the levels.

129. Actual Results, Pennsylvania Railroad Tunnels (A-18) and (A-19).—In order to indicate the accuracy with which tunnels may be driven by shield to a junction under waterways meet. Table XLI gives the results of the closures made on the Pennsylvania tunnels under the East River (A-19) and under the Hudson River (A-18). The figures for the East River tunnels are taken from a paper by Francis Mason, *Harvard Engineerring Journal*, April, 1910.

TABLE XLI.—PENNSYLVANIA RAILROAD TUNNELS UNDER EAST RIVER (A-19) AND HUDSON RIVER (A-18) NEW YORK. LENGTH OF LINE AND ERROR OF CLOSURE

Tunnel	Length of tunnel			Error of closure		
	Tangent, feet	Curve, feet	Total, feet	Line, feet	Level, feet	Distance, feet
East River Line A.....	3,671	269	3,940	0.03	0.017	0.08
East River Line B......	3,629	314	3,943	0.016	0.015	0.08
East River Line C......	3,709	245	3,954	0.01	0.034	0.09
East River Line D......	3,671	285	3,956	0.03	0.031	0.05
Hudson River, North...	6,381	177	6,558	0.041	0.045	0.325
Hudson River, South..	6,380	178	6,558	0.030	0.030	0.328

CHAPTER XVII

COMPRESSED AIR ILLNESS

1. Reason for This Chapter.—This chapter is written for engineers by engineers, as a guide to the precautions and treatment which experience has shown to minimize the illness which is caused by exposure to compressed air. Readers who wish to know more of the physiological features of this illness are referred to the bibliography attached to this chapter. This illness is called "Compressed Air Sickness," "Caisson Disease," "Diver's Palsy" or "The Bends." Unless proper precautions are used on a work where men must work in compressed air, sickness and death will take a heavy toll.

In the large towns where compressed air work previously has been done, it is possible to find doctors who have had practical experience in looking after the health of the working force. In such places no compressed air work should be attempted without the services of such an experienced doctor. In fact it is the custom in the modern specifications for compressed air work to state in so many words that such service shall be provided as part of the work to be done.

Compressed air work is not always done, however, in places where physicians experienced in compressed air work are to be found. Here the engineer must rely upon himself to use such safeguards as experience and science have shown to be necessary. Even in these cases a physician must be attached to the staff but it will be the engineer's duty to see that the proper precautions are taken, the proper treatment given, and the proper records kept. It is for this reason and for this purpose that the following paragraphs are written.

2. Cause of Compressed Air Sickness.—The cause of compressed air sickness is this: "The blood passing through the lungs is in contact with a wet film of protoplasm, which, in its turn, is in contact with the air breathed. The blood takes up the gases of the air in solution and, if exposed to compressed air, will dissolve oxygen and nitrogen in an amount increased pro-

portionally to the pressure." (L. B. Hill, M. B. F. R. S. "Caisson Sickness." 1912, p. 196). The oxygen gas thus taken up, under the ordinary conditions of engineering work in compressed air, has no harmful effect on the body. The trouble is due to the nitrogen gas which is taken in solution by the blood.

While a man continues at work in the compressed air no harmful effects are felt. If reduction of pressure occurs too rapidly the nitrogen held in solution is set free in the form of bubbles. See Fig. 166. These bubbles are taken to the various tissues. The particular portion of the body in which the bubbles are found determine the symptoms exhibited in each case. Speaking in general terms, the higher the pressure, the longer the exposure to pressure and the quicker the decompression, the greater is the chance of illness.

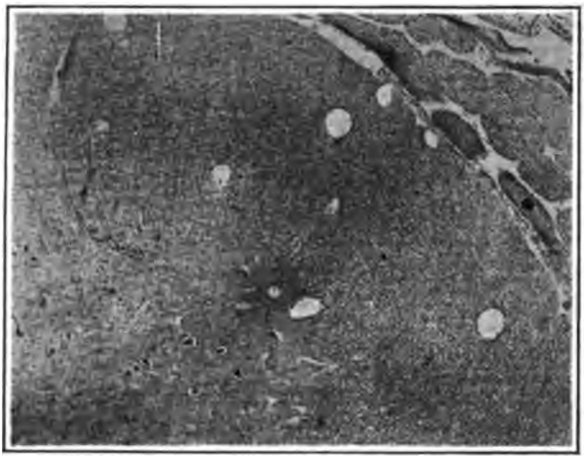


Fig. 166.—Micro-photograph of the section of the spinal cord of a goat killed by sudden decompression. A number of gas bubbles can be seen. From "*Report of a committee . . . on deep water diving.*" London, 1907.

3. Symptoms of Compressed Air Illness.—There are several different manifestations of this illness, depending upon the position of the nitrogen bubbles.

The commonest type of the illness is that known as "The Bends." This is caused by the pressure of the bubbles in the joints of the limbs, and gives rise to pain of an intensely severe degree. In general this symptom may be looked on as a non-dangerous type.

Another form is "The Chokes." This is caused by bubbles in the blood vessels of the lungs giving rise to a form of suffocation. The "Staggers" or "Vertigo" is caused by bubbles in the brain or in the middle ear. Both these types are dangerous.

Collapse, followed by death, is due to quantities of free gas bubbles in the circulation.

4. Precautions.—In order to keep the cases on any piece of work to a minimum certain precautions must be taken. These may be summarized as consisting, in the main, of

(*A*) Examination of each man.

(*B*) Limitation of hours of work.

(*C*) Slow decompression.

(*D*) Avoidance of chill during decompression.

(*E*) Making the men stay near the work for a period after decompression.

Each of these main divisions into which the precautions are here divided are discussed in greater detail as follows.

5. Examination of Each Man.—It goes without saying that the greatest safeguard possible is a physician with previous experience on compressed air work. It is as important and valuable to the medical department of the work to have an experienced doctor as it is to the engineering department to have experienced engineers. It may not be possible to get such a doctor. What then must the doctor look for? What men must he exclude or restrict? In general, he must examine chiefly for (*a*) age, (*b*) fatness and (*c*) blood pressure.

The compressed air worker should be a young man, of spare build and with arteries that have not begun to harden. The reason he should be of spare build is that fatty tissue absorbs about five times as much of the nitrogen gas as the watery tissue and takes, therefore, much longer not only to saturate, but what is more important, to de-saturate.

During the war, the Transit Commission of New York were building several compressed air tunnels across the East River. Since a large number of the sturdy young men were in the army the usual physical standards for compressed air workers had to be lowered. Dr. Levy ("Compressed Air Illness and Its Engineering Importance," page 11) says in this connection. "Actual experience led to the conclusion that, in the selection of men, the essentials are, normal lungs, normal kidneys and a good heart; in the older men the blood pressure must not be high."

When a man has worked in compressed air regularly for 2 months he should be re-examined before being allowed to continue work in the air. Repeat this re-examination of each man at each 2-monthly interval.

When a man is absent from the work for any cause for 10 days or more he should be re-examined before being allowed to enter the air. Record the date and result of each re-examination on each man's examination form. Some men are naturally unfit for work under compressed air under any conditions. This unfitness is not always disclosed by a physician's examination. It is only discovered by the man having several attacks of bends when others do not. Such a man must not be allowed to continue at such work. For this reason it is a good plan not to allow a man who has never worked in compressed air before to go regularly to work until he has worked one-half shift in a moderate pressure—one not over 20 lb.—and to re-examine such a man at the end of this experimental half shift. This precaution will save many a case.

6. Forms to be Used by Physician.—To obtain a full and orderly record of the cases which occur it is essential that each examination and each case be recorded on a carefully drawn form. The following forms have been adopted in the State of New York as a result of conference between compressed air work contractors, the compressed air workers' union, the Public Service Commission and a number of insurance companies. They are given as examples of what should be covered by the records.

(A) Form for Reporting Physician's Examination of Compressed Air Workers

No..................Location...
Name..........................Residence.........................
Age.............Nationality...................Color...............
Single.......Married.....Widower.......Children.......How many.....
Compressed Air Experience.
When..............Where................Experience.............
Compressed air illness.............When..........Character.........
Previous illness.............When.............Character..............
State fully habits with regard to the use of..........................
(*a*) Alcohol...
(*b*) Tobacco..
When last attended by a physician and for what cause.............
....

....
Signature of applicant

Height............Weight..........Sight.............Hearing........
Pulse.....................Character.................................
Is the character of the heart action free and clear?......................
Are its sounds and rhythm regular and normal?.........................
Are there any indications of disease of this organ or of the blood vessels......
Circumference of chest..
(a) Forced expiration................(b) Forced inspiration...........
....
Number of respirations..
Is the respiratory murmur clear and distinct?..........................
General appearance and carriage.....................................
Blood pressure...............(a) Systolic........(b) Diastolic..........
Are the muscular and nervous systems apparently in a healthy state?........
Is there any swelling of the face, abdomen, or lower extremities?............
Has he a hernia?...
What is the specific gravity of his urine?..............................
(a) Albumen...
(b) Sugar...
Full or half shift.
Accepted Rejected
Date .... 192– Remarks........................
..................M.D.
Reexamined................ 192_ Remarks.................. M.D.
Reexamined................ 192_ Remarks.................. M.D.
Reexamined................ 192_ Remarks.................. M.D.
Reexamined................ 192_ Remarks.................. M.D.

(B) Form for Reporting Compressed Air Illness

Location..............................Date......................
Name..................................Check No..................
Address...
Country of birth.........................Color.....................
Age..................Single, Married, Widower, or Divorced..........
Present occupation..
How long has he worked in compressed air?
Date employed by present employer..................................
Present employer...
Present attack..
Air pressure.........................lb.
Time of shifts.
From..........................to..........................
From..........................to..........................
Time of decompression:
First lock...............................minutes.
Second lock.............................minutes.
Character of illness...
....
Onset of illness; Date..............192....Time..........A.M./P.M.

How long after leaving lock did symptoms appear?.....................
Treatment..
Medical-lock decompression:
..........lb. to ....lb. in ....minutes...........
..........lb. to ....lb. in ....minutes...........
..........lb. to ....lb. in ....minutes...........
Relieved: Yes
No
Signed:..

7. Limitation of Hours of Work.—Since the cause of this illness is the taking up of nitrogen gas in the body fluids while under compression, it is natural that there is a relationship between the pressure and the period of time in which saturation of the body fluids with the gas becomes complete. The higher the pressure the less time required to produce saturation. In order to safeguard the worker, therefore, it is proper to limit the hours of work which may be spent by a man in compressed air in each 24-hr. period. The higher the pressure the shorter these hours of work should be. The following Table XLII shows the hours of labor specified in Rule No. 1151 of the New York State regulations (1921).

TABLE XLII.—HOURS OF LABOR PER MAN PER 24 HOURS. NEW YORK STATE RULES

Gauge pressure in working chamber, lb. per square inch	First period of work in compressed air		Period of rest. Normal air		Second period of work in compressed air		Total period of work in compressed air	
	Hr.	Min.	Hr.	Min.	Hr.	Min.	Hr.	Min.
0 to 20	4	00	0	30	4	00	8	00
21 to 29	3	00	1	00	3	00	6	00
30 to 34	2	00	2	00	2	00	4	00
35 to 39	1	30	3	00	1	30	3	00
40 to 44	1	00	4	00	1	00	2	00
45 to 49	0	45	5	00	0	45	1	30

The figures of this table have been plotted and are shown as Fig. 167. This clearly shows how the rules provide for a decrease in the number of hours worked in the compressed air as the pres-

sure in the working chamber is increased and that there is interposed in the middle of the working period a period which must be spent in air of normal pressure and that the length of this rest period increases with an increase of pressure. The object of these periods of return to normal air pressure is to prevent the complete saturation of the blood with the nitrogen gas from taking place.

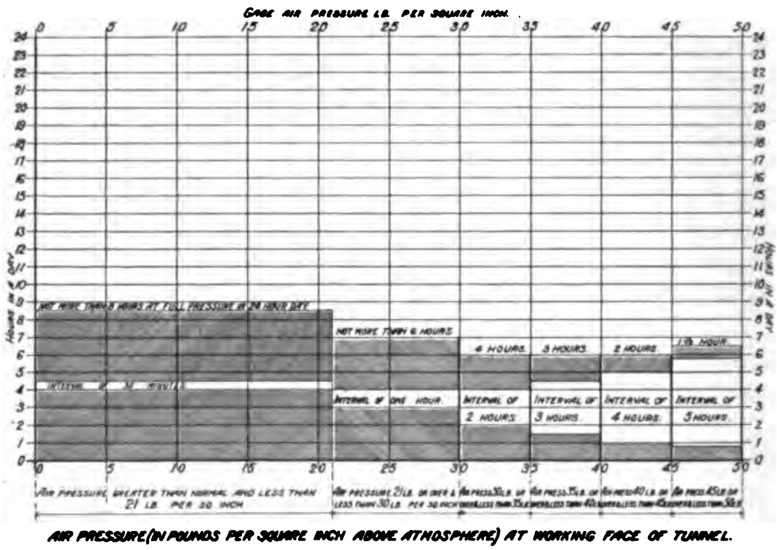


FIG. 167.—Graphical representation of the relationship between the air pressure at the working face and the hours of work per man per day. Industrial Code, Department of Labor, State of New York.

This schedule may seem rather arbitrary in its make-up. It is founded, however, on the experience gained from a great volume of work and may be looked upon as a safe and proper guide for work where the care of the workers' health is a chief concern to those in responsible direction.

8. Slow Decompression.—Since the cause of compressed air sickness is the formation of nitrogen bubbles in the tissues due to a rate of decompression which has been too rapid to permit of the escape of the gas which has been taken up in solution by the body fluids during the stay in compressed air, it follows that the process of decompression must be conducted at a rate slow enough to prevent the formation of these bubbles.

It was noted by Dr. John Scott Haldane, F. R. S. and it is a matter of observation among compressed air workers that no serious cases or practically none, have occurred for rapid decompression when the working pressure has not exceeded 19 lb. per square inch on the gauge, *i.e.*, for 2.3 atmospheres absolute pressure. Haldane argued, therefore (*Journal of Hygiene*, vol. 8, No. 3, June 1908, p. 356). "Since supersaturation to the extent of about 1.25 atmospheres above normal atmospheric pressure can be borne with impunity, it seems clear that, in decompressing after prolonged exposure to high pressures, the rate of decompression should be sufficiently slow to prevent any greater excess of saturation than this in any part of the body at the end of decompression. On the other hand, decompression should evidently be as rapid as possible consistently with safety. A pressure of 1.00 to 1.25 atmospheres above normal corresponds to from 2 to 2.25 times the normal atmospheric pressure; but the volume (*not the mass*) of gas (measured at the existing pressure) which would be liberated if the whole excess of gas present in supersaturation were given off is the same whether the absolute pressure is reduced from 2 to 1 atmosphere, or from 4 to 2, or from 8 to 4. Hence it seemed probable that, if it is safe to decompress suddenly from 2 atmospheres of absolute pressure to 1, it would be equally safe to decompress from 4 atmospheres absolute to 2, from 6 to 3 and so on. Our experiments have shown that this is the case. The process of desaturation can therefore be hastened very greatly by rapidly reducing the absolute pressure to one half and so on, arranging the rest of the decompression that the saturation in no part of the body shall ever be allowed to correspond to more than about double the air pressure."

It was proposed by Henry Japp ("Caisson Disease and Its Prevention," *Trans. Am. Soc. C. E.*, vol. 56, Dec., 1909), that to shorten the period of decompression and at the same time to keep the cases of serious illness down to an almost negligible percentage of the men employed, the limit of 27 lb. gauge pressure be adopted as the safe limit instead of the 19 lb. per square inch used by Haldane. He states that the experience of most tunnel works carried on under compressed air is to the effect that up to 27 lb. gauge pressure there is hardly any real trouble from serious compressed air sickness.

This method of making the decompression in steps is known as

the stage method of decompression. So valuable has the method proved that it is specified now in many compressed air tunnel contracts that, if the pressure in the working chamber is over 22 lb. per square inch on the gauge, there shall be two air bulkheads in use as soon as a certain length of tunnel has been built. The men come out rapidly through the set of locks nearest the working face, in which the pressure is dropped to half the absolute pressure, or perhaps more safely to half the gauge pressure, walk to the second set and come out slowly through this second set. The matter of exercise during decompression is one of great importance and tends strongly toward the diminution of serious cases. This is because the liberation of the dissolved gas is helped by the exercise. (See Hill, *Journal of Royal Society of Arts*, 3041, vol. 59, March 3, 1911.)

This matter of stage decompression is clearly recognized in the Industrial Code, Department of Labor, State of New York, Rule No. 1152, which says

"DECOMPRESSION. No person employed in compressed air shall be permitted to pass from the place in which the work is being done to normal air, except after decompression in the intermediate lock as follows: A stage decompression shall be used in which a drop of one-half of the maximum gage pressure shall be at the rate of 5 lb. per minute. The remaining decompression shall be at a uniform rate and the total time of decompression shall equal the time specified for the original maximum pressure."

For example, suppose the working pressure is 40 lb. per square inch and that there are 2 air lock bulkhead walls some 800 ft. apart.

The men enter the lock nearest the face and pass from 40 lb. to 20 lb. per square inch at the rate of 5 lb. per minute. This takes 4 min. They then walk the 800 ft. through the intermediate chamber at 20 lb. per square inch pressure. This will take them about 5 min. Now they enter the second air lock. They have now taken 9 min. altogether. The rate specified for 40 lb. pressure is 1 lb. per minute, so that, to go from a pressure of 40 lb. to normal pressure, would require 40 min. The men must take, therefore, 31 min. in the second lock to go from 20 lb. pressure to normal, making, with the 9 min. taken to get to the second air-lock, the total required decompression period of 40 min.

A word must be said about the rate of entering the compressed air or "locking in." It is clear from previous paragraphs that the danger of compressed air illness arises on decompression. Many

people unaccustomed to compressed air work will lock in slowly thinking that some danger is avoided in this way. Compression may be done as rapidly as possible. The only limitation is the chance of "getting blocked." The middle ear is an air cavity communicating by a narrow tube, the Eustachian tube, with the back of the nose. If the Eustachian tube does not admit air freely the air pressure in the outer ear becomes greater than that in the middle ear. The membrane of the drum of the ear is pressed inward, the blood vessels of the wall of the middle ear are distended, so that either rupture of the membrane or bleeding is apt to occur. This is not only very painful but may result in temporary or permanent loss of hearing. Different persons vary greatly as to the readiness with which their Eustachian tubes will allow air to pass. A cold in the head may cause almost complete stoppage. By a swallowing movement at the back of the mouth or by holding the nostrils closed and then blowing through the nose it is possible to open the Eustachian tubes and men accustomed to compressed air can do this readily. Beside the middle ear there are other air filled cavities especially around the eyes which communicate with the nose by narrow passages. These may give trouble also if the passages are blocked. Relief is obtained in the same way. Apart from these purely mechanical effects the rate of compression has no effect on the health. It is a good thing, in fact, to go in as quickly as possible as the chance of getting blocked is less and the old hand will go in as quickly as the valve will let him. With a novice it is all right to go in slowly. The roar of the air and the tight-shut steel doors do not make him feel any too comfortable. He does not know how to relieve the blocking which he is almost certain to feel and some few persons cannot equalize the pressure on the ear diaphragm at all and cannot, therefore, go into compressed air.

9. Avoidance of Chill.—It is found to be most important to avoid chill in coming out of compressed air. When the pressure in a lock is reduced the air gets cold, damp and foggy. As it is usually not possible to move about much in the cramped quarters of a lock and as the process cannot be hurried, those who work in compressed air should provide themselves with warm extra clothes to put on when they come out. There is no good reason why the man-lock should not be artificially warmed during the decompression, either by steam, hot water or electricity.

There seem to be, however, but few cases where this has been done.

It is customary to keep a supply of hot coffee on hand for the men when they come out. Any kind of hot drink will do and Dr. Edward Levy (*Safety Engineering*, June, 1920, p. 297) suggests that beef extract cubes, dissolved in hot water would be better than the questionable coffee sometimes served and which, he finds, tends to gastritis. A warm shower followed by a brisk rub down is highly recommended before dressing.

10. Make Men Stay Near Works after Decompression.—On the Pennsylvania Railroad East River tunnels, where 3,692 cases

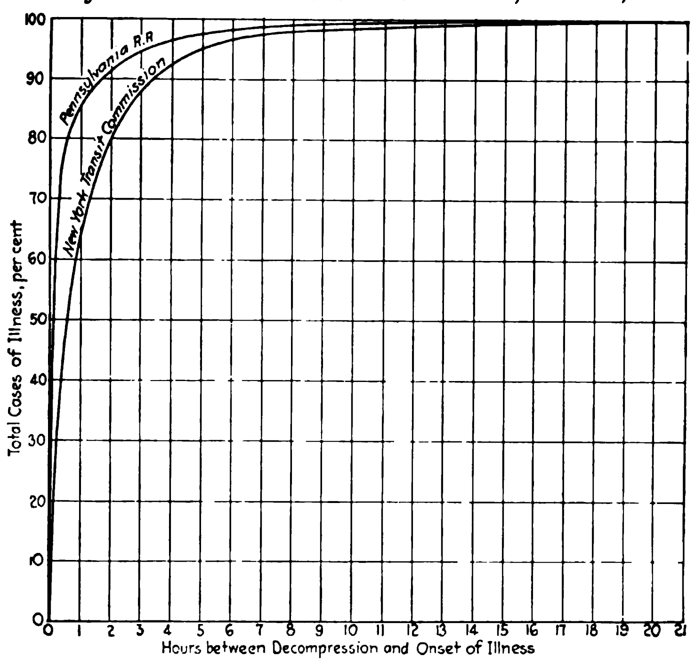


FIG. 168.—Relationship between the hours elapsing between decompression and the onset of illness and the percentage of the total cases of illness. Records of the Pennsylvania Railroad East River Tunnels (A-19) and the East River Tunnels of the New York Transit Commission (A-27, A-28, A-30 and A-35).

were treated 85.9 per cent of the cases occurred within 1 hr. after decompression. On the East River tunnels of the Transit Commission of New York, where 680 cases were treated, 64.2 per cent occurred within 1 hr. In both cases nearly all the really serious cases occurred within an hour after decompression. On the Pennsylvania tunnel work records are in existence showing

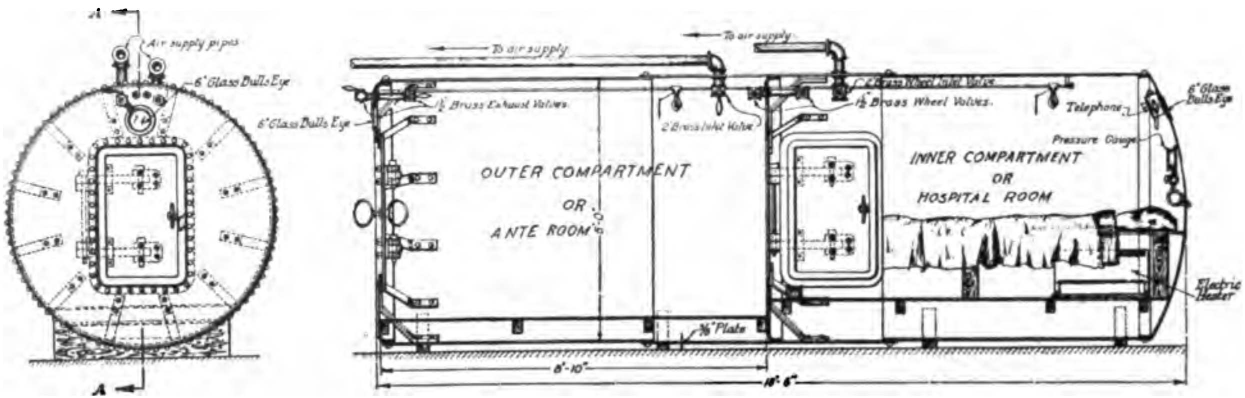
cases which came on 23 hr. after decompression. On the Transit Commission's work the maximum elapsed period was 18 hr. This matter is illustrated graphically in Fig. 168.

Recompression is the only cure as will be described later under par. **11.** This cannot be done except at a place where there is an air lock. Since the recompression should be given at the earliest possible moment a strong effort should be made to induce the men to stay near the works for at least an hour after they get dressed. The great trouble with this, as well as with other rules made for the benefit of the men, is that they seem to look upon them as assaults upon their personal liberty and spend much ingenuity in evading or breaking the rules. If it can be done it is a great thing. It has been found a good plan to provide every compressed air worker with an identification tag with directions on it that, if found sick, he should be taken at once to the works. Many cases of bends look like drunkenness and the unlucky man may find himself taken to some hospital where no one will understand the case or have the means to deal with it and much time will be lost and grave danger incurred thereby.

In some countries there are laws which prevent any one from touching a person found dead, ill or wounded until the police have arrived. Such laws may be a great handicap to the immediate treatment which is so essential. In such countries it is more important than ever to keep the men within the limits of the work for an hour after decompression.

It is dangerous to go to work in compressed air on an empty stomach. In the early days of the Havana Sewer tunnel (C-1) across the Harbor an undue number of cases were reported. It was found that the Cubans came to work unfortified by anything more than a cup of coffee. The contractor thereupon arranged to give the compressed air men a good breakfast free of charge before they went down. The cases at once showed a marked drop. This story may be worth noting for use in countries where the Anglo-Saxon type of breakfast does not hold sway.

11. Cure for Compressed Air Illness.—There is only one cure. This is recompression to the same pressure as that in which the man has been at work, reducing to the half pressure fairly rapidly but not so quickly as in the tunnel and from the half pressure to normal at a rate which is at least twice as slow as that prescribed for the actual work in the tunnel.



END VIEW

SECTION A-A.

END VIEW OF EXTERIOR AND SIDE VIEW OF INTERIOR OF MEDICAL LOCK

FIG. 169.—A modern "hospital" or "medical" lock. As used on the East River Tunnels of the New York Transit Commission. (Courtesy of *Transit Commission, New York.*)

For the purpose of giving this treatment the "Medical" or "Hospital" lock is used. Such a lock is shown in end elevation and longitudinal section in Fig. 169. The lock shown is that used on the East River tunnels of the New York Dual Subway System. These tunnels were built in the period from the year 1914 to the year 1921 and this type of medical lock may be taken as representative of the latest practice.

The lock, in effect, consists of an ordinary tunnel air lock but is divided in two compartments by an intermediate diaphragm and door. The outer compartment forms an ante room to the inner one. The inner compartment is the hospital in which the patient is placed while under compression and decompression. By means of the ante room the physician may enter or leave the hospital compartment at any time without disturbing the pressure of the air in that portion. The lock is provided with electric lights, telephone, clock, pressure gauge, thermometer, electric heater and medical equipment such as cot, blankets, basin, water etc. It is arranged so that ventilation may be effected. The air pipes and valves are arranged so that the pressure in each of the compartments may be regulated from the outside and that the pressure in each compartment may be regulated from the next compartment. The pressure in the hospital compartment may be regulated by its own valves. There is a glass bulls eye window in each door arranged in line so that the patient, the pressure gauge and the thermometer in the hospital compartment may be seen from the outside.

The treatment consists in placing the patient in the hospital compartment, making him as comfortable as possible and raising the pressure to that in which he has been working. The pressure is then dropped to half, at a rate twice as slow as prescribed for this operation in the tunnel itself. The pressure is then lowered to that of the atmosphere also at a rate twice as slow as that prescribed for the tunnel. In most cases, if the patient has been placed in the medical lock soon after the symptoms have appeared, a perfect cure will be made by this process. If a cure has not been made the patient should be recompressed and decompressed still more slowly and it may be necessary for the physician to administer some stimulant if the vitality is low. Sometimes recompression has to be done three or four times before permanent relief is given. If the patient can do so he should move about and exercise the affected part during decom-

pression. In severe cases an attendant should give massage. In unconscious cases artificial respiration should be performed.

The great thing is promptitude in recompression. A few minutes may mean the difference between life and death. Hence the huge importance of finding a way to keep the men at hand. close to their means of safety, after they have come from work,

12. Purity of the Air.—It is important that the air supplied to the compressed air chambers shall be clean and free from impurities and that it shall be cooled.

The air intake, through which the air is drawn into the air compressors, is set up above the roof of the compressor house and its mouth covered with wire gauze so that no large pieces of dirt may be drawn in. After compression the air is taken into the coolers, as the process of compression raises the temperature of the air.

In the coolers most of the lubricating oil which becomes mixed with the air during its passage through the cylinders of the compressors is separated. The air is then led to the receiver, a large vertical tank, which serves the purpose of damping down the pulsations due to the strokes of the air compressor pistons. The air is led into the top of the receiver and taken out at a point about one-third of the height of the tank from the bottom. In this way the air, during its passage from the top of the tank toward the lower outlet, deposits the oil and moisture which the coolers have failed to remove. From the receiver the air passes into the tunnel piping system.

For years it was thought that the amount of carbon dioxide gas (CO_2) in the tunnel air had much to do with the bends. It is quite certain that this is not the case. Nevertheless undue amounts of this gas do have painful effects on those breathing it. Make a daily analysis of the tunnel air at the working place. If the proportion of CO_2 gas is more than 1 part in 1,000 parts of air, take steps to improve the ventilation not on account of the bends, but because larger percentages are harmful anywhere.

Carbon monoxide is a deadly gas which has a tremendous affinity for the hæmoglobin of the blood, so that, if breathed even in small quantities, the blood becomes unable to take up the necessary amount of oxygen. This gas is given off by dynamite used in blasting rock. The amount varies with the quality and make of the explosive. If blasting has to be done, take special

care to see that fresh air is supplied close to the working face and clear the working place of gas immediately after firing the shot by opening the exhaust before allowing the men back at work.

13. General Precautions.—Several general rules for the safeguarding of health should be stated as they are not specifically covered in the foregoing paragraphs,

(*A*) Use a recording gauge to show the rate of decompression on each man lock.

(*B*) Test all gauges once a day.

(*C*) Use a good competent man as lock-tender.

(*D*) See that the decompression of each man is recorded.

(*E*) Keep the tunnel and locks in an absolutely sanitary condition.

(*F*) Allow no smoking in compressed air.

(*G*) Allow no animals (other than men) in compressed air.

(*H*) Give each man an individual clothes locker.

(*I*) Provide a drying room for wet tunnel clothes.

(*J*) Provide hot and cold shower baths.

(*K*) Provide wash basins with hot and cold water.

14. Records of Number and Types of Cases.—To show the progress made in combating this illness during the last few years, the following pages contain the available statistics as to the number of cases and of death which have occurred, expressed in terms of the number of decompressions made. A mere recital of the number of cases which occurred on this, that or the other tunnel conveys no useful knowledge. A certain piece of work might show twice as many cases as another and yet be much more free from illness when the total number of decompressions that were made was taken into account. For this reason be careful, on any piece of work, to keep proper record of the number of decompressions made. Have the lock-tender, or assign some one else, to make a record of the name and number of each individual man who is decompressed with particulars as to the pressure, time taken for decompression and the limits of pressure between which the decompression takes place.

Moir has said (*Proc. Inst. C. E.*, vol. 150, p. 55) that when he came to New York in the year 1890, to look after the work on the old Hudson Tunnel (A-6) resumed by an English company after Haskin's financial failure, he found that "the men had died at the rate of 25 per cent per annum and nobody had seemed to care anything about it." He devised and used the first hospital

lock on the old Hudson Tunnel and tunnel men should honor his name for this inspiration.

It is a pity that the statistics which follow are so meagre in number. The reason is that, while figures are available in some cases of the total number of cases and of deaths, no record is given of the number of decompressions involved. The cases are confined, therefore, to those of the Pennsylvania Railroad tunnels under the Hudson and East Rivers at New York, built between the years 1904 and 1909, and those of the Transit Commission of New York, built between the years 1914 and 1921.

The Pennsylvania Railroad tunnels were built before the present New York State regulations had been framed. Such rules as existed were those evolved by the engineers and contractors concerned, acting with the advice of their medical officers.

The hours of labor on the Pennsylvania tunnels were as follows: In pressures of from 1 to 31 lb. per square inch above normal the men worked 4 hr. in the pressure, had half an hour out for lunch and worked 4 hr. again in the pressure. For pressures between 32 and 42 lb. per square inch the men worked 3 hr. in the pressure, came out for 3 hr. and worked again for 3 hr. The rules about decompression were rather vague. For pressures up to 32 lb. there was a rule that 10 min. should be taken for decompression. The rate was left entirely to the men, however, who came out as fast or as slowly as they wanted. On the East River work of the Pennsylvania some regulation was done when the pressure became exceptionally high. After a good deal of careful observation on that work the following was done when the pressure reached 40 lb. Three sets of air locks were used. The inner chamber was kept at 40 lb. pressure, the intermediate at 29 lb. and the outer one at 12½ lb. The men were ordered to take 5 min. in the first lock, 8 min. in the second and 15 in the third. There was about 1,000 ft. between the locks. This distance took 10 min. for each pair of locks, so that 48 min. were taken to decompress from 48 lb. to atmosphere. Under this pressure 330 men worked for 36 days, working 3 hr. on, 3 hr. off and 3 hr. on. No severe or fatal cases occurred and such cases as were treated were slight (Japp. *Trans. Am. Soc. C. E.*, vol. 65, p. 21).

On the tunnels of the New York Transit Commission the hours of labor, rates of decompression and so on were as regulated by

the New York State regulations which have been described before. It is interesting to see the difference which those regulations have made. Table XLIII tells the story.

TABLE XLIII.—COMPARATIVE STATISTICS OF COMPRESSED AIR ILLNESS ON THE EAST RIVER (NEW YORK) TUNNELS OF THE PENNSYLVANIA RAILROAD AND OF THE TRANSIT COMMISSION AND OF THE HUDSON RIVER (NEW YORK) TUNNELS OF THE PENNSYLVANIA RAILROAD

Item	Hudson River, New York,	East River, New York	
	Pennsylvania Railroad tunnels	Pennsylvania Railroad tunnels	Transit Commission tunnels
Date	1904 to 1909	1904 to 1909	1914 to 1921
Maximum air pressure	37 lb.	42 lb.	48 lb.
Number of decompressions	190,000	557,000	1,361,461
Number of cases	550	3,692	680
Ratio of cases to decompressions	1 in 346	1 in 151	1 in 2,002
Number of deaths	1	20	2
Ratio of deaths to decompressions	1 in 190,000	1 in 27,850	1 in 680,730
Type of case, as % of total cases:			
Local pain in body	94.45%	90.33%	91.7%
Vertigo	Moderate, Severe 2.18%	5.33%	6.5%
Central nervous system	Severe 2.37%	2.16%	1.6%
Chokes		1.62%	0.1%
Collapse		0.46%	0.1%

The Pennsylvania Railroad Tunnels under the Hudson and under the East River were built at the same time and under the same general rules as to working hours and so on. The generally better showing made by the Hudson River tunnels may be ascribed to the fact that the average air pressure on those tunnels was about 26 lb. whereas on the East River it was about 35 lb. On the Transit Commission East River tunnels shown in the last column the average air pressure was also around 35 lb.

The percentage of slight cases (ordinary "Bends") is remarkably alike in these three sets of figures and it seems as though, for pressures up to 48 lb. per square inch a percentage of some 92 or 93 of slight cases may be expected, and that under modern regulations and treatment the death rate is only 1 in nearly 700,000 decompressions. One of the severe cases on the Hudson River Pennsylvania tunnels happened under the low pressure of 22 lb. after a shift of 8 hr. The decompression rate in this case was probably too fast although we have no figures on this point.

If we take the ratios shown in Table XLIII and consider those obtained on the Transit Commission tunnels as represented by unity, the following figures are given.

TABLE XLIV.—PROGRESS IN SAFETY FROM ILLNESS IN THE LAST TEN YEARS

Tunnel, New York	River	Date	Ratio of	
			Cases to decompression	Deaths to decompression
New York Transit Commission	East	1914–1921	1.0	1.0
Pennsylvania Railroad	East	1904–1909	13.25	24.5
Pennsylvania Railroad	Hudson	1904–1909	5.79	3.58

This table shows that there is now from one-sixth to one-thirteenth the chance of incurring illness that there was 10 yr. ago, and that the chance of death is now from ¼ to 1/24 what it was 10 years ago, provided the best known practice is followed as regards the hours of labor, rates of decompression and other modern safeguards.

For pressures between 40 and 45 lb. Table XLV is instructive.

TABLE XLV.—CASES AS PERCENTAGE OF DECOMPRESSIONS FOR PRESSURES FROM 40–45 LB.

Tunnel	River, New York	Date	Number of Decompressions	Gauge pressure lb. per sq. in.	Number of cases	Number of cases as percentage of decompressions
Pennsylvania	East	1904–1909	8,510	40	139	1.63%
Transit Commission	East	1914–1921	5,325	41	5	0.094
Transit Commission	East	1914–1921	8,456	42	12	0.142
Transit Commission	East	1914–1921	5,730	43	6	0.105
Transit Commission	East	1914–1921	4,702	44	1	0.021
Transit Commission	East	1914–1921	33,085	45	24	0.073
Total Transit Commission	....	1914–1921	57,298	41–45	48	0.084

In other words for a pressure of 40 lb. in 1904 to 1909 there were about twenty times as many cases per unit of decompressions as in 1914 to 1921 for pressures up to 45 lb.

15. Analysis of Types of Illness.—Dr. Edward Levy (Bureau of Mines *Technical Paper* **285**) gives the following analysis of the

cases on the Transit Commission East River Tunnels. Of the 624 cases of localized pain 335 cases, or 49.3 per cent of the entire number, showed one joint only affected; in 251, or 36.9 per cent of all cases, there was multiple involvement; in 38, or 5.6 per cent of all cases, there were body or head pains. Only one case of localized pain, which was in the abdomen followed by collapse, was fatal. This was after exposure to a pressure of 33 lb. followed by decompression taking 22 min.

The knee is the most usual place for the localized pain. For example, in the cases of single joints affected, out of 335 cases 209 were in the knee. In the cases of multiple joints affected, out of 251 cases, 91 were in the two knees and some other part also.

There was one case of "Chokes," which followed a too rapid decompression. The attack came on 2 hr. after decompression and the man died an hour later.

Both fatal cases were followed by autopsies which showed large quantities of free gas in all veins.

16. Numbers of Cases in Various Pressures.—Dr. Levy (in *Technical Paper* 285 of the Bureau of Mines), gives the following information with respect to the cases which developed under each pound of pressure on the East River Tunnels of the Transit Commission at New York. They are quoted here in order to give a standard of comparison on future work.

TABLE XLVI.—FROM ATMOSPHERIC PRESSURE TO 22 LB. INCLUSIVE PER SQUARE INCH ABOVE. 4 HR. IN, ½ HR. OUT, 4 HR. IN.

Gauge pressure, pounds per square inch	Number of decompressions	Number of cases	Number of decompressions for each case of illness	Cases of illness as percentage of number of decompressions
1 to 14	188,496	none	infinite	0.0
15	73,956	1	73,956	0.00135
16	17,625	1	17,625	0.00569
17	93,333	1	93,333	0.00107
18	45,256	2	22,628	0.00443
19	66,997	4	16,749	0.00599
20	70,605	4	17,651	0.00568
21	65,074	3	21,691	0.00462
1 to 21	621,342	16	38,834	0.00258

All these cases were trivial.

TABLE XLVII.—FROM 22 TO 29 LB. GAUGE PRESSURE INCLUSIVE. 3 HR. IN, 3 HR. OUT, 3 HR. IN

Gauge pressure, pounds per square inch	Number of decompressions	Number of cases	Number of decompressions for each case of illness	Cases of illness as percentages of number of decompressions
22	19,187	0	infinity	0
23	24,018	3	8,006	0.0125
24	17,009	10	1,701	0.0589
25	23,239	5	4,648	0.0215
26	42,458	19	2,234	0.0449
27	35,827	29	1,237	0.0810
28	102,851	96	1,071	0.0936
29	56,092	139	403	0.248
22 to 29	320,681	301	1,062	0.0945

All these cases were trivial.

TABLE XLVIII.—FROM 30 TO 34 LB. GAUGE PRESSURE INCLUSIVE. 2 HR. IN, 2 HR. OUT, 2 HR. IN

Gauge pressure, pounds per square inch	Number of decompressions	Number of cases	Number of decompressions for each case	Cases of illness as percentage of number of decompressions
30	28,538	14	2,038	0.0492
31	56,291	36	1,563	0.0642
32	41,356	37	1,120	0.0895
33	63,846	50	1,275	0.0785
34	75,111	113	665	0.1505
30 to 34	265,142	250	1,060	0.0945

TABLE XLIX.—FROM 35 TO 39 LB. GAUGE PRESSURE INCLUSIVE.
1½ HR. IN, 3 HR. OUT, 1½ HR. IN

Gauge pressure, pounds per square inch	Number of decompressions	Number of cases	Numbers of decompressions for each case	Cases of illness as percentage of number of decompressions
35	20,816	16	1,300	0.0770
36	8,629	8	1,077	0.0930
37	5,048	3	1,680	0.0596
38	9,972	3	3,320	0.0302
39	13,252	11	1,206	0.0831
35 to 39	57,718	41	1,406	0.0713

TABLE L.—FROM 41 TO 44 LB. GAUGE PRESSURE INCLUSIVE.
1 HR. IN, 4 HR. OUT, 1 HR. IN

Gauge pressure in pounds per square inch	Number of decompressions	Number of cases	Number of decompressions for each case	Cases of illness as percentage of number of decompressions
41	5,325	5	1,065	0.0625
42	8,456	12	705	0.1420
43	5,730	6	955	0.1048
44	4,702	1	4,702	0.0213
41 to 44	24,213	24	1,009	0.1000

TABLE LI.—45 LB. GAUGE PRESSURE.
¾ HR. IN, 5 HR. OUT, ¾ HR. IN

Gauge pressure pounds per square inch	Number of decompressions	Number of cases	Number of decompressions for each case	Cases of illness as percentage of number of decompressions
45	33,085	24	1,378	0.0727

The figures of these Tables XIVI to LI are shown graphically as Fig. 170.

17. Conclusion.—If the suggestions given in this chapter are followed, the best practice of modern times will be assured. Clearly it is to the advantage of the engineering profession, on the basis merely of the promotion of that profession, to say nothing of the ordinary motives of humanity, to see that the cases of compressed air illness are reduced to the minimum in number and in severity and that the method of treatment at hand shall be the best that experience has proved. If work in compressed air bears the reputation of bringing to those engaged in it a great risk of death or of terrible and perhaps life-long suffering then such work will be undertaken only with the greatest

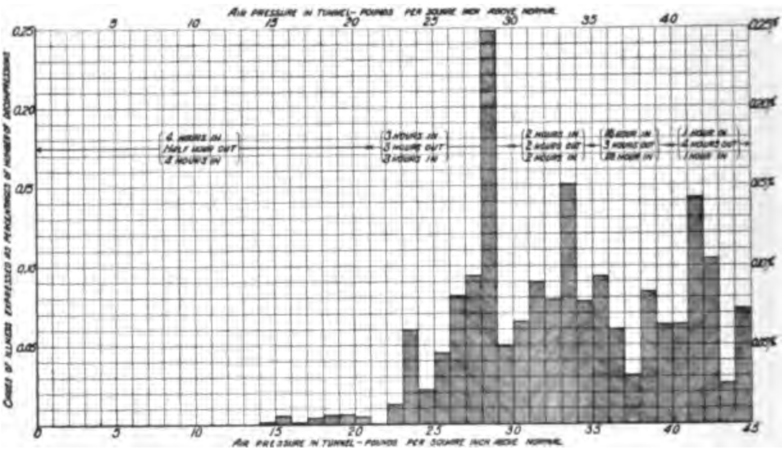


Fig. 170.—Relationship between the air pressure at the working face and the cases of illness expressed as percentages of the number of decompressions from that air pressure.

reluctance by those whose responsibility it is to decide upon and to direct it. When it is begun, the only ones who will work upon it will be the reckless adventurers who are willing to take any chance, especially if coupled with the high pay offered for such hazards. If, on the other hand, the work is conducted so that the risks of suffering and death are reduced to such an extent that only a small percentage of the decompressions result in suffering and practically none in death then it will be more freely undertaken and it will attract to itself the best and most skilled class of labor.

Give the physician in charge a large degree of responsibility and authority. He should report directly to the Engineer in

charge or to the contractor himself or the chief responsible officer as the case may be. His word should be absolute in his department. Give him enough medical assistants so that a qualified physician is on duty for every moment of the time that work in compressed air is in progress and enough clerical assistance that a full and complete written record of the medical history of the work may be available. No scientific progress is possible in any line of work without full written record. The engineer's interest lies in making possible work at higher pressures than those attempted in the past. The only way this can be done is to see that the best qualified physician is retained and that he is encouraged to investigate and record the cases in the fullest degree.

Follow infractions of the rules as to rates of decompressions by the instant dismissal of those guilty. It is worse than useless to have carefully drawn rules treated as a dead letter. Make the men understand that the rules are there for their benefit and to save them from suffering and death and let no familiarity with the dangers be allowed to breed contempt for the safeguards provided.

The following is a list of books and papers which have been published on this subject. It does not pretend to be a complete bibliography and it is confined in general to writings in the English tongue. No attempt can be made to discriminate between the references in order of use and importance but it is natural to suppose that the most recent publications carry the fruits of all previous investigation. The references are listed in the chronological order of their appearance.

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